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# ELEMENTS
OF
# OPTICAL MINERALOGY

## AN INTRODUCTION TO
## MICROSCOPIC PETROGRAPHY

WITH DESCRIPTION OF
ALL MINERALS WHOSE OPTICAL ELEMENTS ARE KNOWN
AND TABLES ARRANGED FOR THEIR DETERMINATION MICROSCOPICALLY

BY

ewton orace
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WITH 350 FIGURES IN THE TEXT
AND 4 PLATES

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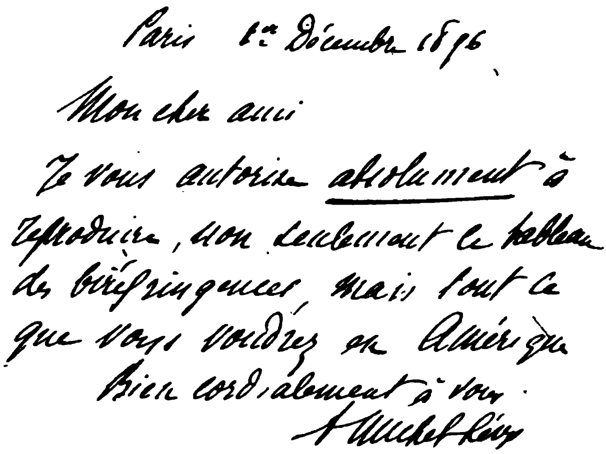

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Bien cordialement à vous

A Michel Lévy

# PREFACE

When the preparation of this volume was first undertaken some years ago, there was not in the English language a systematic treatise on the subject of microscopic petrography which was adapted to the needs of students. It seemed a little singular and most unfortunate that the language, in which at the hands of Sorby modern petrography had its birth, should not possess a clear and concise presentation of its principles, methods, and data. The best treatise then available was a translation of a German text, which suffered from the defects inherent in translations, and from the cumbrous and highly involved grammatical constructions of the German original, too frequently retained in the translation. The work of the French petrographers, now for several years in the front rank, was then, and still remains, available only in French. Furthermore, there is not extant in that language an elementary treatise on microscopic petrography. The accurate and remarkably useful methods which were devised by Fouqué and Michel Lévy are to be found only where the savant would search for them, and when so found they are likely to be buried so deeply in mathematical demonstrations that they cannot easily be apprehended.

More recently several admirable English treatises on microscopic petrographic methods have appeared in America, namely those of Luquer, Iddings, and Johannsen. Without disparagement to these it is still true that the principles, methods, and data of optical mineralogy have not yet been presented concisely and clearly in any single publication. It has been the aim of the authors to supply that deficiency, and to supply it in that form which would be most useful to the student.

This work had its inception under the impulse of a conviction that English students and independent workers in petrography needed a clear and systematic description of the apparatus to be used and the methods to be employed. The aim has not been to write a treatise on optics, nor upon crystallography, but the elements of these subjects have been presented only so far, and as briefly, as is consistent with a comprehension of the main theme, which is the microscopic study of minerals and rocks.

More recently the original manuscript has been revised after being put to the test of use, and some improvements and en-

192765

largements have been added, the chief of which is the alphabetically arranged descriptions of all minerals that are identifiable with the microscope. The work claims but little that is original, beyond the manner of condensation and presentation. Being practical teachers, the authors know the difficulties of both teacher and student, and have had both in mind in its preparation. The advanced student will note, however, new illustrations of the effect of crystals upon light, new drawings and results in the discussion of the feldspar group, and new tables for the determination of minerals microscopically. It has been the aim to bring the tables and descriptions of minerals up-to-date, and to include in them all minerals whose optic characters are sufficiently well-known to permit their determination microscopically. This is a feature that should be of special value to those engaged in studying ores, veins, or any deposits containing not merely the ordinary rock forming minerals. It is believed that with this work at hand the independent worker, even in advanced research, will have directions for practically all microscopic tests, and all necessary data concerning any minerals he may encounter.

The authors have made free use of the published works of Michel Lévy, Fouqué, and Lacroix. To the last named they are both under special obligations. They have also constantly consulted the works of J. D. and E. S. Dana, of Hintze, Rosenbusch, and the other well-known authors on mineralogy. They have adopted from Iddings the use of the letters X, Y, Z, to represent the axes of ether vibration in biaxial crystals.

Probably no words are needed to justify the exclusive use of the Miller symbols in referring to crystal faces and forms.

Special thanks are due to Professor U. S. Grant, of Northwestern University, for critical suggestions, and for the laboratory illustrations of Part I, which in the main are adopted from his manuscript notes.

Professor C. E. Mendenhall, of the University of Wisconsin, kindly revised the chapter devoted to the phenomena of light, and to him the authors are indebted for some exact definitions of the movements of light.

N. H. Winchell,
Alexander N. Winchell.

December 1, 1908.

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# ELEMENTS OF
# OPTICAL MINERALOGY

## PART I.

## PRINCIPLES AND METHODS.

The use of the petrographical microscope involves a knowledge of two subjects, and hence an introduction to microscopic petrography may be divided into two chapters:

1. *Certain phenomena of light.*
2. *Elements of mineralogy.*

The refinement of microscopic manipulation in modern petrography consists almost solely in making accurate application of the phenomena of light to the varying structures of the six crystallographic systems of mineralogy. Hence a third chapter would consist of:

3. *Application of polarized light to crystalline substances.*

## CHAPTER I.

### CERTAIN PHENOMENA OF LIGHT.

The phenomena of light, which are of special importance to the student of petrography, are:

*Reflection.*
*Refraction.*
*Polarization.*
*Absorption.*

LIGHT is a form of energy, and may be produced by transforming other forms of energy into extremely rapid vibration of a medium called the *ether*, which is assumed to pervade all space, existing in all parts of all fluid and even all solid bodies. There must be some medium for the transmission of energy through interplanetary spaces, and it has been found that this energy is carried in the same way, and therefore doubtless by the same medium, through the atmosphere and through liquid and solid bodies. But the phenomena of transmission are modified by the molecular structures of solid bodies, and especially by that of crystalline bodies.

Propagation of Light: The transmission of light is accomplished by means of motion of the ether, and this motion in its simplest type is a vibration back and forth in planes at right angles to the direction of transmission of the light. This may be more readily understood by considering the motion of any particle of water when a wave-motion is produced on a quiet surface by dropping a stone into it. Any particle of the water moves straight up and down, but the impulse or wave-motion moves outward horizontally in all directions from the center of disturbance. So in the case of light the wave-motion moves in straight lines in all directions from the source of light, but this is accomplished by means of vibrations of the ether in directions perpendicular to the direction of propagation. This may be graphically illustrated, as in figure 1. Here *A B* represents the direction of propagation of the light and *C p F m D* represents one complete wave. The distance *C D* is therefore the *wave-length*, which may be described as the distance from one particle to the next in the same *phase*, i. e. in the same relative position and moving in the same direction. The motion of each particle is only in one straight line perpendicular to the direction of propagation. Thus the particle at *p* will move downward to *p′* as the wave advances. These two points are equidistant from the point of rest for this particle, which is on the line *A B*. The *amplitude of vibration* is the distance from the point of rest to the point where the particle reverses its direction of motion; that is, it is one-half the distance *pp′*. The *intensity* of the light varies with the square of the amplitude, but the *color* of the light depends upon the wave-length. Thus ordinary white light consists of waves of all wave-lengths from that of violet to that of red.

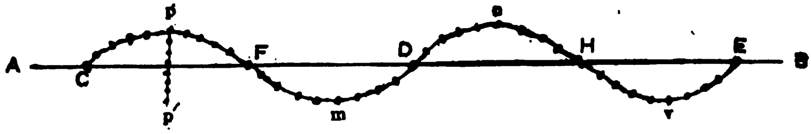

Fig. 1. Propagation of Light.

Wave-front. If a light disturbance starts from any source, it spreads out in the form of a wave. A locus of points in which the disturbance is in the same phase is a wave-front.

Light Ray. A light ray is a succession of points forming a line in the path of a light wave such that the disturbance at any one point is predominantly due to the disturbance at the preceding points. If the disturbance at any point, say *B*, is due to the disturbance at *A*, then *A* and *B* are on the same light ray. Also, the light ray from *A* to *B* is found to be the path of shortest time of passage from *A* to *B*.

If a light disturbance spreads out from a single point source through a homogeneous isotropic medium a wave front will be a spherical surface increasing in radius as it passes away from the source. When the radius has become great enough (in ordinary cases some hundreds of feet—in more precise cases some miles) a portion of the spherical wave can be treated as a plane wave. When a wave front passes through a boundary surface from one isotropic * medium to another, the form of the wave front is changed, so that in general a spherical wave is no longer spherical. If the original disturbance had spread into an anisotropic medium, the form of the wave front would depend upon the special nature of the medium.

Reflection: When light reaches the boundary between media of different density it is usually in part turned back or reflected. This reflection does not cause the light to return along its original path, except in the case of light striking a reflecting surface perpendicularly. But it is true at all times that the angle of reflection is equal to the angle of incidence. (fig. 2.) Furthermore, the incident and reflected light-rays both lie in the same plane with the normal to the reflecting surface at the point of incidence.

Refraction: For a general figure to illustrate single refraction, draw a circle about the point *A*, at which a ray of light traversing the common air, encounters a horizontal surface *D C* of another isotropic medium (water) of greater density than air. Let *G H* be a perpendicular diameter of the same circle. The ray *B A* will be divided at *A* into two parts: one part *A F*, will be reflected, as already explained, at an angle ($r$) equal to the angle ($i$) at which the ray falls on the surface of the denser medium. The other part, *A E* will pass into the other medium, but suffers a deflection from its course, dependent upon its direction and the difference of density of the two mediums, being bent

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* For a definition of the terms isotropic and anisotropic, see p. 12.

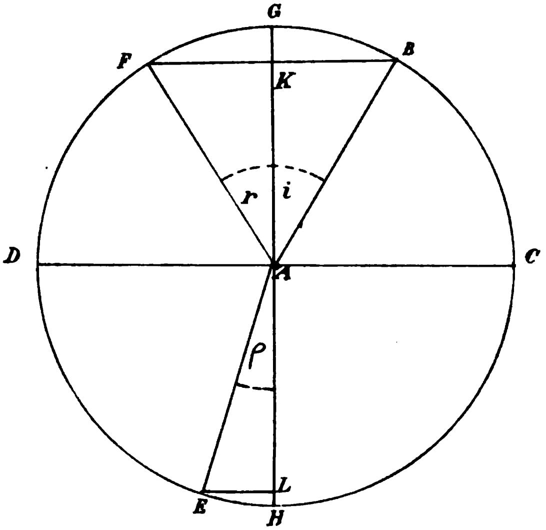

Fig. 2. **Reflection and Single Refraction.**

toward the vertical *G H*. The angle *E A H* is called rho ($\rho$), or

THE ANGLE OF REFRACTION: It is obvious that this angle is in the same plane as the angles of incidence and reflection, which may be distinguished by letters *i* and *r* respectively. If, in such conditions, a ray pass from a denser to a lighter medium the refraction of that part which enters the lighter medium would be away from the perpendicular *G H*. There is in general no refraction if the ray is perpendicular to the surface at *A*.

The angles of incidence and of refraction, for the same substances, have an important and constant relation to each other, whatever may be the direction of the incident ray.

INDEX OF REFRACTION: Thus, the sine of *i* (*KB*) divided by the sine of $\rho$, (*EL*) constitutes the *index of refraction,* which is a property often of use in determining mineral species. Ordinarily the *index of refraction,* of a given medium, is computed when the incident ray passes from atmospheric air into that medium, the variations of temperature and barometric pressure being unimportant. The *index of refraction* is conventionally represented by *n*.

If some other medium be employed than air, the index of refraction of the substance in air will be the product of its index in the medium by the index of that medium in air.

## INDICES OF REFRACTION OF VARIOUS SUBSTANCES.

| | |
|---|---|
| For ice | $n = 1.310$ |
| For water | $n = 1.336$ |
| For alcohol | $n = 1.36$ |
| For common glass | $n = 1.435$ |
| For olive oil | $n = 1.47$ |
| For Canada balsam | $n = 1.536 — 1.549$ |
| For rock salt | $n = 1.544$ |
| For quartz | $n = 1.547$ |
| For methylene iodide | $n = 1.75$ or 1.74092 at 16° C. |
| For diamond | $n = 2.270$ |
| For sphalerite or zinc blende | $n = 2.369$ |
| For rutile | $n = 2.712$ |

For air at the temperature of freezing and with a barometric pressure of 760 mm., compared with a vacuum, $n = 1.000294$.

Light of different colors has different indices of refraction, owing to the varying length of the light-wave. The index of refraction for the colors near the violet side of the solar spectrum is greater than for those near the red side. In practice, however, where the different colors of the spectrum are shown, comparison is made usually of the violet ($v$) with the red ($\rho$). The intermediate colors are seldom mentioned.

Total Reflection: The phenomenon of *relief* as observed under the microscope, is due to high refraction, as when a ray of light passes from a section, say of olivine, into the air. In this case the ray is refracted *away* from the perpendicular. Let the ray *A O* (fig. 3) strike the upper surface *L M* of the olivine section at the point *O*. Then it will be refracted along the line *O D*. If the direction of the incident ray coming from the condensing lens be, instead, represented by *A′ O*, on reaching *L M* the refraction might be along the line *O L*. But if the direction of incidence of the ray be such as to make any angle less than, say *A′ O M*, as *A″ O M*, then the ray will be totally reflected at O, in the direction *O C* and lost to the observer.

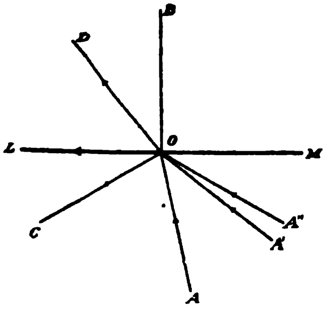

Fig. 3. Total Reflection.

It is obvious that this total reflection increases with the refractive index and for rutile would be greater than for olivine. It is most observable about the edges of any mineral section.

*Laboratory Illustration*: Small fragments of minerals having different refractive indices should be viewed, immersed in balsam on a slide, and notice taken of the difference of relief. Quartz and oligoclase have practically the same refractive index as the balsam, but topaz, hornblende, olivine, augite, epidote, zircon and rutile form an ascending scale with increasing relief, often showing a marked shagreen.

DETERMINATION OF THE INDEX OF REFRACTION. There are several methods of determining the index of refraction, but for the petrographer the following described two methods are probably the most useful. That of duc de Chaulnes has been improved by Sorby,* and is very commonly referred to.

Suppose an object ($O$) to be in the focus of the objective of the microscope, the rays from which enter the objective without passing through any other medium than common air. If then a transparent thin section of glass ($M$) be interposed between the object ($O$) and the lens of the microscope, it will appear that the tube of the microscope must be raised a short distance in order to bring the object again into focus, which may be at $p$. This is due to the fact that all rays from $O$ are refracted away from the normal ($o\ b$) on emerging from the thin section, as illustrated by the figure for the rays $o\ c$ and $o\ k$.

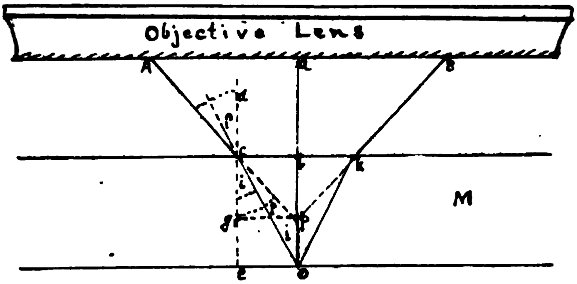

Fig. 3a. Chaulnes Method.

In the adjoining figure let $d\ e$ be perpendicular to $c\ b$ and parallel to $a\ o$. Then the ray $c\ o$ will have $i$ for its angle of incidence at $c$, and $e\ o$, or its equivalent $c\ b$ for its sine and $c\ e$, or its equivalent $b\ o$, or its cosine. As the tangent is the equivalent of the quotient of the sine divided by the cosine, then

$$\tan i = \frac{cb}{bo}$$

---

* Min. Mag. II. 1. 103. 1878.

The same ray will have $\rho$ for its angle of refraction. Its sine is $g\ p$, or its equivalent $c\ b$. Its cosine is $c\ g$ or its equivalent $b\ p$. Then

$$\tan \rho = \frac{cb}{bp}$$

Dividing,

$$\frac{\tan i}{\tan \rho} = \frac{bp}{bo}$$

As the tangents have the same ratio as the sines,

$$\frac{\sin i}{\sin \rho} = \frac{bp}{bo} = n$$

Therefore the index of refraction for a ray emerging into air at $c$ is the ratio of the thickness of the plate ($b\ o$) divided into the thickness of the plate as reduced for the new focal point ($b\ p$). For a ray passing from air into the plate $i$ and $\rho$ obviously are interchanged, and

$$n = \frac{bo}{bp}$$

The distances $b\ o$ and $b\ p$ can be measured by the micrometer screw.

In the place of glass any transparent mineral section could be substituted with practically the same results, but in the case of a doubly refracting mineral the rays $E$ and $O$ would have to be investigated separately.

Other methods of determining the index of refraction are more exact. They are based on the angle of total reflection for the substance, and on the Becke method of observation described below.

Fragments of transparent crystals are immersed in a heavier liquid whose index of refraction can be raised or lowered by the addition of another liquid. In that way the Becke line, between the liquid and the fragments, can be caused to disappear, which indicates that the liquid and the fragments have the same refractive power. The index of refraction of the liquid is then to be determined. When the orientation of any observed fragment can be noted, as the direction of X or Z, the refractive index $n_p$ or $n_g$ may be determined. Otherwise this observation determines only some index between the limits $n_g$ and $n_p$.

The angle of total reflection has been employed in different devices for determining the index of refraction. The refractometers of Bertrand and of Smith are specially adapted to the examination of fragments upon which a plane surface exists or can be cut, and hence are adapted to the examination of gems.

Smith's refractometer is illustrated by the adjoining figure.* The specimen to be examined is applied, by its smooth surface, to the flat surface of a hemisphere of dense glass having a refractive index of 1.7902, and so inclined to the axis of the instrument that the center of the field corresponds to a refractive index of 1.61. At the eyepiece of the instrument a scale is seen within, across which falls the line separating darkness from light, i. e. the line limiting total reflection for the substance under examination. From the scale the index is read directly to the second place of decimals, and the intervals are such that the tenths of each can be estimated.

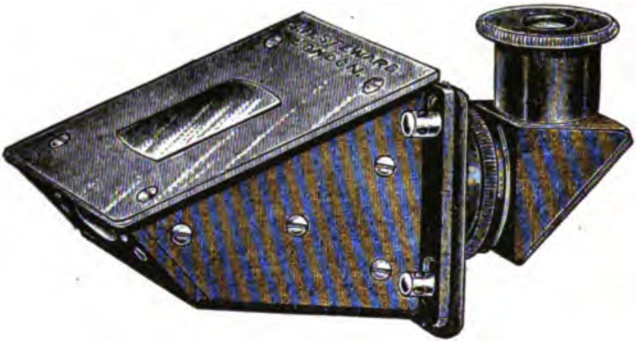

**Fig. 3b. Smith's Refractometer (actual size.)**

The most exact method of applying total reflection to the determination of the index of refraction requires a liquid of higher index than the mineral in question. In this the mineral is suspended, or fixed on a suitable holder, its reflecting surface vertical. It is rotated about a vertical line situated in the reflecting surface, and its position of total reflection of a beam of light that strikes the reflecting surface normal to the vertical line in the reflecting surface, is read through a special telescope whose axis is also perpendicular to the line about which the crystal rotates. The angle of rotation from total reflection in one position to total reflection in another. the two being in adjacent quadrants, is read on a horizontal graduated circle. These points are obviously on opposite sides of the axis of the observing telescope. The total rotation is double the angle wanted.

---

* Mineralogical Magazine, vol. xiv, p. 355, 1907.

Figure 3 c illustrates the use of this apparatus. It represents a horizontal section passing through the vessel containing the heavier liquid, coinciding with the axis of the observing telescope. The plates $c$ and $d$ represent two positions of the reflecting surface at the instants of total reflection, $N$ is the normal of the surface $d$ and $N'$ is the normal to the surface $c$ at the corresponding moments of time. It is plain that, since total reflection occurs when the angle of refraction, $NOD$ or $N'OC$, is 90°, the axis of the observing telescope $OT$ is the line of the incident ray for both observations and that the total angle of rotation, $NON'$, is double the angle of incidence.

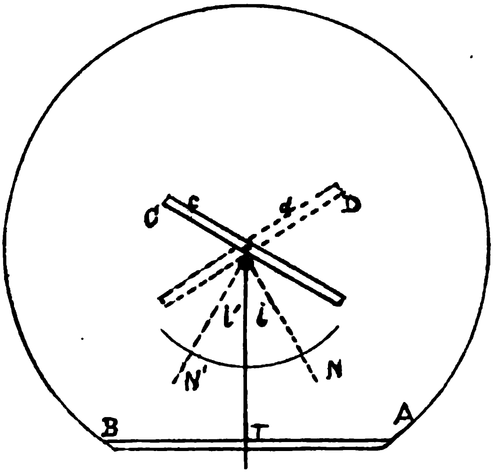

**Fig. 3c. Kohlrausch's Apparatus.**

Since

$$n = \frac{\sin i}{\sin \rho}\text{, if } \rho \text{ is } 90^\circ \text{ then } n = \frac{\sin i}{1} = \sin i \text{ for air.}$$

Allowing $x$ to represent the refractive index of the liquid (p. 5.), the value of $n$ for the mineral is expressed by the formula

$$n = x \sin i$$

The examination should be made in monochromatic light, yellow (sodium) being preferable and usually most readily available. For a table of the refractive indices of various liquids and solids see p. 5.

If the reflecting surface is parallel to the optic axis of a uniaxial mineral both its indices may be determined from the two angles of total reflection that will be observed; if it be normal to a bisectrix of a biaxial mineral similarly it permits the determination of two of the indices of the mineral.

*Determination of relative values of indices. The "Becke method."* It sometimes happens that two adjacent mineral grains in a thin section cannot be distinguished from each other by any obvious characters, though belonging to different species. They can be distinguished by what is known as the "Becke method," by a comparison of their refractive indices. This very delicate and reliable test is at the same time quite simple. It involves the use of total reflection in connection with refraction.

In convergent light, with a high power objective (Nachet No. 7) bring the focus directly upon the line of separation of the two mineral grains.* On lowering the condenser and removing the analyzing nicol the field is a little darkened, but a very fine line of white light, clearer and brighter than the grain on either side, accompanies sharply the line marking the contact of the two grains. When the objective is focused so that the line is bright, if the objective be raised very gently, and the least amount possible, this bright line moves a little toward the more refractive mineral. If the objective be lowered in the same way the white border shifts a little toward the less refractive mineral. This method is most useful for distinguishing between orthoclase and quartz, and especially between acid and basic plagioclases as compared with quartz. It is to be employed with one caution, viz.: when two adjacent minerals of nearly the same refractive index happen to be cut, one perpendicular to X and the other to Z, the movement of the bright line might be governed by the difference between $n_g$ and $n_p$ rather than by the difference of their mean refractive indices.

The phenomena of this method have been explained by W. O. Hotchkiss,** and from his explanation the following is condensed.

*A B* is a vertical section through a thin rock-section, showing two minerals whose plane of contact is represented by the line *Y Z*, *B* having the greater index of refraction. Four rays of light, ascending from the convergent lens, are represented by 1, 2, 3, 4 at incident angles on *X Y* of 45° and 20°. Without refraction they would meet at *O*. If the refractive indices of *A* and *B* are 1.50 and 1.70 respectively, since the sine of the angle of incidence at total reflection is the reciprocal of the refractive index, the angle of total reflection for *B* is 62° 10′. Therefore the rays 3 and 4 will be totally reflected on striking the separating plane *Y Z*, at *m′* and *n′*, their angles of incidence being greater than 62° 10′. The rays 1 and 2 passing through *A* are not totally reflected on reaching *Y Z*, since *B* is denser than *A*, but they are partially reflected at *m* and *n*, and partially refracted into *B* as shown, the amount reflected depending on, whether the plane of contact between *A* and *B* is polished or rough, on the size of the angle of incidence and on the difference between the indices of *A* and *B*. The result is that in all cases there is a preponderance of light on the side of that mineral having the higher index of refraction when the objective is focused on the surface of the section or on any point within the section from the surface to *m′*. It is obvious, from the direction of the refracted and reflected rays, that on raising the focal point within this interval the bright line broadens and moves toward *B*, but on lowering it the line is moved toward *Y Z* and brightened; if the focus be lowered to a point, which may be represented by *m*, the brightest light appears on the side of the mineral of the lower index. This is

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* For a description of the microscope and its parts see p. 41 and figure 54.

** American Geologist, vol. xxxvi, p. 305, Nov. 1905.

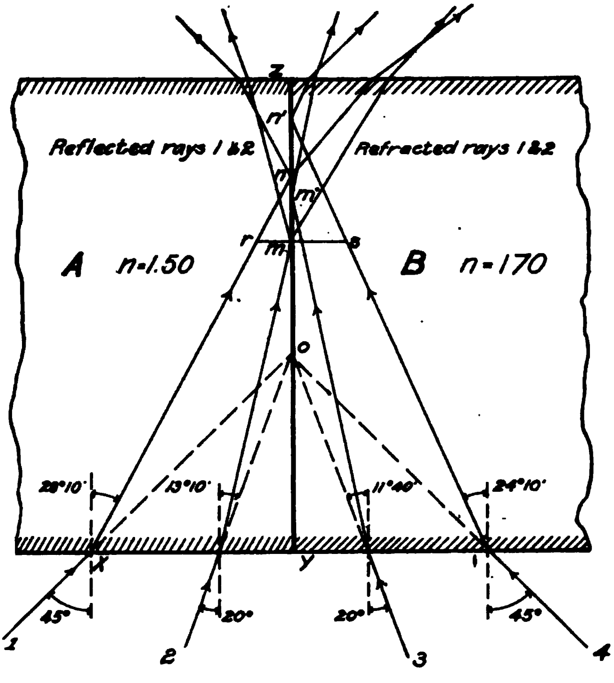

**Fig. 3d. The Becke method.** ***Hotchkiss.***

explained by the fact that the light in *A* (rays 1 and 2) is concentrated within the space ***mr,*** but the light in *B* (rays 3 and 4) is extended over a broader interval, ***ms.***

*Inclined illumination.* When the mirror is shifted out of the axis of the microscope or one side of the beam of light from the mirror is shaded by any means, the light and shade on the two sides of two substances of different refringence are even more pronounced than in the method described above, as Becke himself has stated. The cause of the phenomenon is easily understood by a study of figure 3e, in which the mineral *A* is surrounded by a mineral *B* of higher index of refraction. Now an inclined beam of light passing from *B′* into *A* is made narrower, or condensed, by refraction away from the perpendicular, while a similar and parallel beam of light passing from *A* into *B* is refracted toward the perpendicular and therefore dispersed. Consequently, when the edge appears bright (as in passing from *B′* to *A*) the mineral of higher index is on the side whence the light comes, and when the edge appears dark (as in passing from *A* to *B*) the mineral of lower index is on the side whence the light comes.

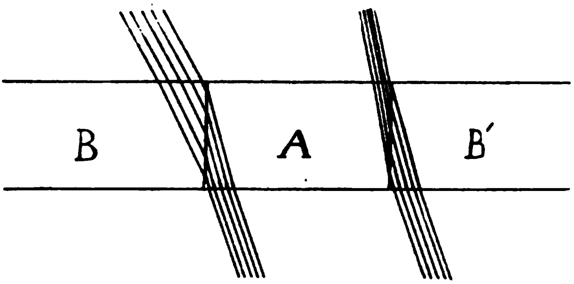

**Fig. 3e. Inclined Illumination.**

In using this method it may be noted that, though the direction of inclination of the beam of light is reversed by the substage lenses, it is counteracted by the reversal of the image in the microscope. Hence the phenomena may be read as though no change of inclination took place.

Isotropic and Anisotropic Substances. All substances capable of transmitting light are divided into two classes; viz. isotropic and anisotropic.

In *isotropic* bodies light passes with equal velocity in all directions. Such are gaseous, fluid, and amorphous bodies, as air, water, glass; also those which crystallize in the isometric system.

In *anisotropic* bodies light passes with greater velocity in certain directions than in others. Such bodies crystallize in any one of the five other systems of minerals.

Single refraction takes place in *isotropic* bodies and double refraction in *anisotropic.*

## *Refraction in Anisotropic Media.*

Owing to the greater number of rock-forming minerals belonging to the crystalline systems here included, and especially to the triclinic and monoclinic systems, the processes and principles of double refraction, and the polarization which results from it, possess the highest importance and utility in microscopic petrography.

NATURE OF DOUBLE REFRACTION: When a ray of light from an isotropic medium enters an anisotropic medium, at whatever angle, its vibrations are made to conform to the molecular structure of the latter, and it advances in accordance with the ease of the light movement possessed by the latter. It is at once divided into two rays polarized at right angles to each other, and travelling in different directions; one is the ordinary ray (*O*), so-called because it follows the laws of single refraction, and the other the extraordinary ray (*E*), which does not follow the laws of single refraction; when the original ray enters the anisotropic medium perpendicular to its surface the ordinary ray passes directly through without refraction, if the surface of exit is parallel to the surface of entrance, but the extraordinary ray is diverted.* On leaving the substance, however, the two parts resume parallelism, but with the waves of one slightly in advance of the other. If these rays are then brought into parallel vibration, as by passing through the analyzer, the two sets of waves interfere, producing light of different colors. This is the circumstance on which rests most of the work done in examining minerals in thin section in parallel polarized light.

If on emerging from such anisotropic body, the plane surface separating the media at the point of exit be oblique to the direction of the oppositely polarized rays, or to the direction of either of the refracted and polarized portions, such plane acts as a refracting agent in accordance with the comparative density of the two media, in the same manner as in single refraction.

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* If the incident ray is perpendicular to the surface and parallel with an optic axis, there is no refraction nor polarization; and if perpendicular to the surface and to an optic axis, there is no refraction, but there is a division into two rays travelling at different rates and polarized at right angles to each other.

The index of refraction of the ordinary ray is expressed by the Greek letter omega ($\omega$), and that of the extraordinary ray by epsilon ($\epsilon$).

Polarization. With an ordinary beam of waves of light, the character of the disturbance produced by the waves as they pass any point is such that during the shortest time which we can use in experimenting the disturbance has no fixed *direction* or *character*. That is to say, during this time the ether is subject to the *same average displacement* in *all directions*. With a *polarized* beam of waves the disturbance *at a point* is fixed in character,—i. e., is permanently *linear* in a *definite direction,* or *elliptical* or *circular,* as the case may be.

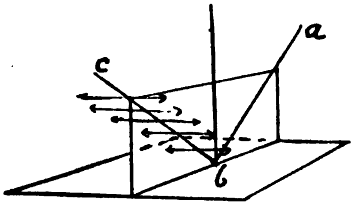

**Fig. 4. Polarization by reflection.**

In the first case it is referred to as a *plane polarized* wave. Light may be thus polarized by reflection, or by refraction, or, in some cases, by transmission without refraction.

By Reflection. An ordinary beam of light waves, incident (not normally) on a non-metallic reflecting surface may be considered as *resolved* into two, one vibrating perpendicular and one parallel to the plane of incidence. These two component beams will (with ordinary light) be of equal intensity before incidence, but will be reflected in different proportions, so that in the reflected beam vibrations normal to the plane of incidence will predominate. Thus, fig. 4, a beam, *a b,* reflected from a polished plate glass at *b,* has a part of its vibrations brought into a single direction, as indicated by the arrow points, and this direction is perpendicular to the plane of incidence and reflection.

By Single Refraction: Most of the processes of microscopic petrography involve light polarized by refraction.*

Light may be *singly* or *doubly refracted.*

In the case of single refraction, the light of the refracted ray is partially polarized in a plane at right angles to the plane of polarization of the reflected ray. The maximum polarization in both refracted and reflected rays occurs when these are at right angles to each other.

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* This is the customary statement, but it should be remembered, as stated under refraction that polarization may take place in a transmitted ray without refraction.

By Double Refraction: The two rays are completely polarized in all cases of double refraction, in planes at right angles to each other.

The eye cannot distinguish polarized light from ordinary light. Indeed most of the light that enters the eye is already partially polarized, resulting from the refraction and reflection which it suffers from surrounding objects. The angles and degrees of reflection are so numerous and so various that a general diffusion of light takes place, instead of any unique change referable to a single reflection. It is only when a bundle of rays are gathered from this confused mass and given uniform direction as by the mirror of the microscope, and passed with precision through some of the foregoing experiments that light may be proven to possess the quality of polarization.

## THE NICOL PRISM.

In the nicol prism, or simply the nicol, which is an essential part of every polarizing microscope, advantage is taken of the divergence of the ordinary and extraordinary rays, to isolate the latter for use in the examination of minerals. This is done in the following manner:—

Iceland spar, which is simply a pure and very transparent form of common calcite, the principal ingredient of limestone, readily cleaves in three directions. Hence it is easy to obtain inclined prisms, more or less elongated in one direction. The

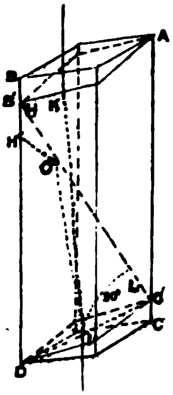

Fig. 5. Side View of the Nicol Prism.

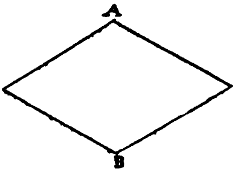

Fig. 6. End View of the Nicol Prism.

end cleavages are inclined 71 degrees to the obtuse edges of the prism. The side view of such a prism is represented by figure 5, *A B C D*. The end faces are then reduced by grinding and polishing until they make an angle of 68 degrees with the obtuse edges. The prism then would have the form *A B′ C′ D*. It is then carefully cut into two parts along the plane *H L* perpendicular to the shorter diagonal of the end face. The cut faces, after polishing, are cemented together again in their original position by Canada balsam, which has nearly the same index of refraction as the Iceland spar. It is then covered by a black coating of some kind. The end aspect, when completed, is shown by figure 6, in which the line *A B* represents the shorter or ***principal*** diameter, parallel with which are the vibrations of the extraordinary ray.

When a ray of light enters the prism at *I* the prism is so adjusted that the extraordinary ray is refracted into the direction *I K* and emerges parallel with its original direction, at *K*. The layer of balsam does not essentially disturb its direction, but the ordinary ray *I O*, polarized at right angles to the extraordinary ray, has so large an angle of incidence on the balsam layer at O, and so high an index of refraction that it is totally reflected and lost against the blackened surface of the prism at *H′*. The vibrations in the extraordinary ray are parallel to the shorter diameter, or to the ***principal optic section*** of the nicol prism. (See a more detailed description pp. 47 and 48).

Nicol prisms are also sometimes made of different shape; thus, they may have the rhombic vertical edges ground off until the cross section is a square whose sides are parallel to the diameters of the rhomb; again, they are sometimes so constructed that the extraordinary ray is totally reflected, and the ordinary ray passes through. A given microscope may even have its two nicols of unlike construction, but the complete plane polarization of the transmitted light is accomplished in all cases.

Every petrographical microscope has two such artificial prisms; one below the stage, in the axis of the microscope, called the ***Polarizer*** and one above the objective, called the ***Analyzer***. The essential quality of these prisms consists in their power to eliminate the ordinary ray which vibrates parallel with the longer diagonal of their end faces, and to allow the passage of the extraordinary ray which vibrates with the shorter diagonal. They are inserted in their places in such a way that the lower and sometimes the upper can be easily rotated horizontally on their axes, or removed entirely. In the figure of the Nachet microscope (fig. 54) the analyzer is outlined in the position which it has when lifted from its place in the body of the microscope.

ABSORPTION: This term implies that some part of a beam of light is lost in being reflected from or on passing through any medium, but in many minerals the amount thus lost is so slight as to be imperceptible. The color of any object, whether by transmitted or reflected light, is due to the combined effect of those wave-lengths, or colors, which are not absorbed. A few minerals, as epidote, show different colors, (*e. g.*, yellow and green) in common light, according as the direction of the light is related to the crystallographic axes. But many minerals show this character distinctly only with polarized light. Thus, hornblende will appear green if polarized light vibrating parallel to $Z$ (approximately its elongation) passes through it, and yellowish if the vibration is perpendicular to this direction.

The term absorption strictly is applicable to the amount of light absorbed, irrespective of the resultant color.

The term selective absorption or pleochroism is applicable to those cases in which any mineral in polarized light presents different colors, depending on the relation of its axes of ether vibration to the direction of vibration of the transmitted light.

Selective absorption, therefore, results in:—

*Dichroism,* when a mineral shows two colors only.

*Trichroism,* when it shows three colors.

*Pleochroism,* is a general name including both the preceding.

An *Absorption Formula* is an expression of these different amounts of absorption in any mineral; thus $a>b$ indicates that absorption is greater when the ether vibrations of the polarized ray are parallel to the crystallographic axis $a$ than when they are parallel to $b$. But absorption is usually stated in terms of the chief optic directions instead of crystallographic axes.

A *Pleochroic Formula* expresses, in a similar manner the colors that a mineral presents in polarized light vibrating parallel to each of its axes of ether vibration.

## CHAPTER II.

## ELEMENTS OF MINERALOGY.

It is unnecessary and impracticable to give here a complete account of the physical and crystallographic characters of minerals. It is intended at this place only to call attention concisely to the essential characteristics of each crystal system, not including the properties that can be illustrated by the use of polarized light. The differences which these systems manifest in polarized light are given in the following chapter.

This, however, in order to be intelligible and entire, must be founded on elementary definitions of terms and accompanied by some necessary fundamental principles of crystallography. The student who desires further knowledge is referred to the larger works, such as those of Dana, Mallard, Lewis, Liebisch, Moses, or Story-Maskelyne.

### DEFINITIONS AND ELEMENTARY PRINCIPLES.

Certain conventional terms and symbols illustrative of general principles that appertain to all systems, will here be defined.

AXES: Figure 7 represents the normal position of a crystal as discussed in mineralogy, with its axes *a, b, c*. Such crystal forms may be rectangular or oblique, and the axes may be perpendicular or oblique to each other at *O*. It is obvious that there are eight portions or octants which are symmetrically placed about *O*. Unless otherwise indicated that octant which is situated in the upper right-hand corner in front of the observer, is the one to which mineralogical definitions refer. It is the only one embraced wholly within the positive arms of the axes.

The angles between the axes *a, b, c,* when not 90° are denoted by the corresponding letters of the Greek alphabet, thus $a \wedge b$ by $\gamma$, $a \wedge c$ by $\beta$, $c \wedge b$ by $\alpha$.

The planes in which any two of the axes co-exist are called *axial planes*.

PARAMETERS: Although crystals are not generally simple and rectangular, as represented by the fundamental figure (fig. 7), but have external plane surfaces that cut the axes in different directions and at various distances (as *ABC*), yet a condensed

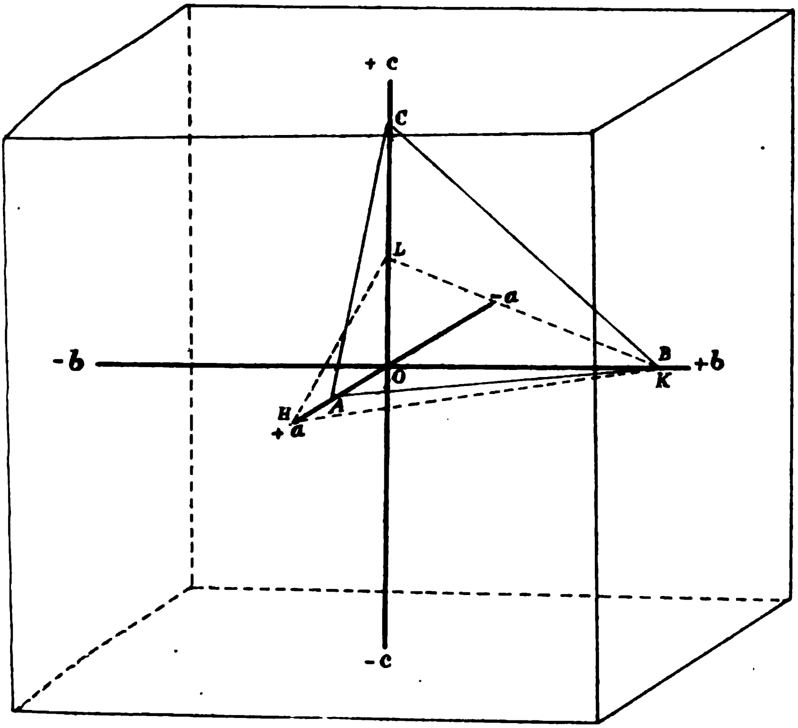

Fig. 7. Axes and Octants.

uniform system of nomenclature for all planes has been adopted. It is obvious that any surface plane of a crystal may be shifted parallel with itself, either nearer the center *O* or to a position further removed from *O*, and that it would intercept the axes *a*, *b*, *c* (or—*a*,—*b*,—*c*) at distances from *O* which would have between themselves the same numerical ratios. The same is true of all the plane surfaces. That is to say, whatever be the size of any crystal the intercepts of its planes on its axes have the same ratios as its homologous planes at unit distances. Hence it is necessary only to ascertain and express these ratios in order to completely define the form of a crystal. In figure 7, let the plane *ABC*, be supposed to intercept the axes at their unit lengths.

Then $OA : OB : OC$.

or

$a : b : c$, as $1 : 1 : 1$

in which the figures 1, 1, 1, are the parameters of the plane *ABC*.

If $A$ is at the center of the line $HO$, and $L$ at the center of the line $CO$, and $K$ is the same point as $B$, another plane $HKL$ can be passed through these points whose ratios would be $2a:1b:\frac{1}{2}c$. As the axes are always expressed in the same order, they may be omitted, and this plane may be written 2 : 1 : ½. The axis $b$ is usually taken as unity, and the other axes are expressed in fractional parts or in multiples of it.

INDICES: When these fractional ratios are reduced to integers the expression is simpler still, and the foregoing becomes 4 : 2 : 1, or simply 421. The expression 124 in which the figures are the reciprocals of 2, 1, ½, reduced to integers, indicates the plane $HKL$, according to Miller's system of nomenclature, and these figures are known as the indices of that plane.

The plane at the extremity of the axis $b$ is known as the plane $b$ or 010. That at the negative extremity would become $0\bar{1}0$, in which the figure 0, in each case, indicates that the plane considered is parallel with the axes $a$ and $c$; the symbol 001 is Miller's expression for the plane at the positive extremity of the axis $c$, and 100 indicates that at the positive extremity of the axis $a$.

In order to define a crystal plane it is, hence, necessary to know the numerical ratios existing between its intercepts on the axes of the crystal to which it belongs. Experience has shown that all the planes of any crystal, as well as all the planes of all the crystals of any mineral, can be expressed either by small multiples of unity, or by these combined with infinity or with its reciprocal, zero.

PLANES OF SYMMETRY: If a crystal can be divided by an imaginary plane into two parts such that one will repeat the other in the manner that an object is reproduced when in front of a mirror, such plane is a *Plane of Symmetry*. Some crystals have numerous planes of symmetry, and some have none. Axes of symmetry are normal to planes of symmetry and about them a crystal may be supposed to revolve, bringing the crystal into identical crystallographic positions two or more times in a complete revolution. Such axes of symmetry are usually chosen as the crystallographic axes, and they are also often the axes of ether vibration.*

The term CRYSTAL FORM is used technically to include all the planes of a crystal which may be derived from any known plane according to the symmetry of the class and system to which it belongs. Thus, by reference to figure 7, if the plane *H K L* be known to belong to the orthorhombic system, the necessary *crystal form* would require the presence also of the other planes surrounding the point *O*, namely:

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*A principal plane of symmetry is one about whose normal axis the crystal may be revolved less than 180° and still bring the crystal into identical crystallographic position. Such planes only exist in crystals of the isometric, tetragonal and hexagonal systems.

$$\bar{H}KL \quad \bar{H}\bar{K}L \quad H\bar{K}L$$
$$HK\bar{L} \quad \bar{H}K\bar{L} \quad \bar{H}\bar{K}\bar{L} \quad H\bar{K}\bar{L}$$

and for the symbol 124 the following planes are required to complete the form:

$$\bar{1}24 \quad \bar{1}\bar{2}4 \quad 1\bar{2}4$$
$$12\bar{4} \quad \bar{1}2\bar{4} \quad \bar{1}\bar{2}\bar{4} \quad 1\bar{2}\bar{4}$$

If the form belong to the tetragonal system it requires 16 planes. If it belong to the isometric (or cubic) system it has 48 similar planes; if to the triclinic, it has only two. (See further under the different systems.)

Pinacoids are forms whose planes are parallel to two of the crystallographic axes. Two such are seen in the tetragonal form, fig. 8. These pinacoidal faces have special names in the different crystallographic systems. A single pinacoid cannot inclose space.

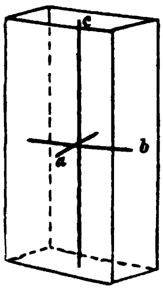

**Fig. 8. Pinacoids of the Tetragonal System.**

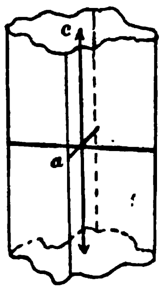

**Fig. 9. Prism.**

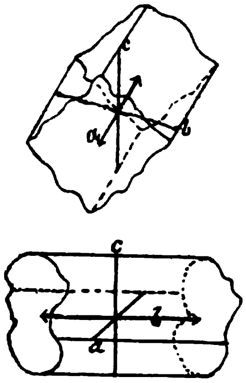

**Fig. 10. Domes.**

A Prism is a crystal form whose planes are parallel to the vertical axis, and intersect both the horizontal axes, as figure 9. It is not a closed form.

Domes are forms resembling prisms but in transverse position, having their planes parallel to one of the lateral axes. Figure 10 represents two domes; one having its planes parallel to *a* and the other to *b*, which are not closed forms.

It is evident that it is a matter of arbitrary choice, so far as outward form is concerned, whether figure 9 represents a prism or a dome.

Pyramids are forms whose planes intercept all three of the crystallographic axes,—figure 11. These are closed forms except in the monoclinic and triclinic systems.

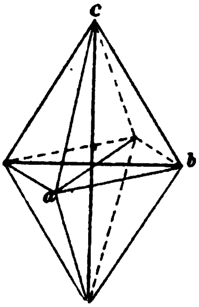

Fig. 11. **Pyramids.**

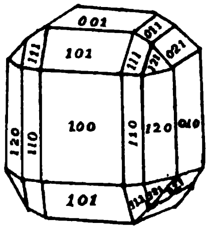

Fig. 12. **General Figure Showing Crystal Forms.**

In the general figure (fig. 12) the sides 100, 010 and 001 are pinacoidal faces, or simply pinacoids; 110 and 120 are prismatic faces or prisms; 101 is a macrodome, being parallel to the greater of the lateral axes; 011 and 021 are brachydomes, being parallel to the shorter lateral axis, and 111, 121 are pyramidal faces or pyramids.

Combinations. When any of the above crystal forms do not enclose space they unite with others of the same system and grade of symmetry. A single crystal, therefore, may contain prisms and pyramids, or pinacoids and pyramids, etc. It is found that in nature such combined forms have common axes which possess the same axial ratios as the separate forms. Certain forms prevail in nature; the lateral pinacoids, for instance, being developed, as in some feldspars, at the expense of all the other planes. In other minerals the prisms sometimes prevail, giving rise, in

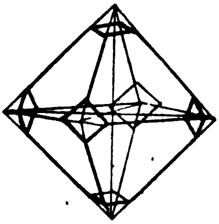

Fig. 13. **Combination of Cube and Octahedron.**

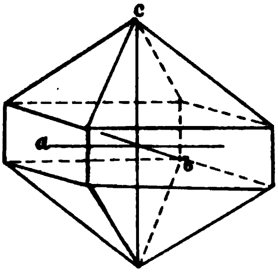

Fig. 14. **Combination of Prism of the Second Order and Pyramid.**

like manner, to very long and even acicular crystals, or fibres as in chrysotile.

When two forms combine, whether closed or open, having axes of different lengths, their faces and angles mutually intercept each other, as in figures 13 and 14. If the axes in fig. 14, were diagonal, the figure would show a combination of the prism and pyramid, the former, however, being an open form.

**Fundamental Form** is that form which is assumed as the starting-point in the development of any crystallographic system, and to it are referred the numerical calculations necessary to compute the axial ratios. In the rectangular crystallographic systems; viz: the isometric, the tetragonal, the hexagonal and the orthorhombic, the fundamental form, when all its planes are present, is a solid body; viz: respectively, the octahedron, the teragonal pyramid, the hexagonal pyramid, and the orthorhombic pyramid, Their pyramidal planes cut all the axes at their unit lengths, except in the hexagonal system, where they each cut three and are respectively parallel to the remaining fourth axis. Any such pyramidal plane could be chosen to construct the fundamental forms (p. 20). In the monoclinic and triclinic systems a pyramidal face is chosen such that the axes *a* and *c* may be parallel to some prominent planes.

**Spherical Projection**: For the purposes of definition and calculation the surfaces and the angles of crystals are supposed to be transferred to the surface of a sphere, as in figure 15. The centre of this sphere is at the point at which the crystallographic axes meet. Radii are drawn perpendicular to the several planes of the crystal. The points at which these radii meet the surface of the sphere are called *the poles* of the various planes of the crystal. It is customary to consider only one hemisphere which should be that in which occur the poles of those planes most useful for reference and most commonly met with.

In fig. 15 the poles of the prismatic faces 110 and $1\bar{1}0$ are at *D* and *E*. The pole of the pinacoid 100 is at *A*, and that of 001 is at *C*. It is obvious from an examination of fig. 15, that the arcs on the circumference of the sphere, as *A D*, measure angles at *O* which are the supplements of the angles included between the planes of the crystal of which *A* and *D* are the poles.

The angles between the radii drawn to poles, and hence the interfacial angles of the crystal can all be computed by the methods of spherical trigonometry. Similar projections can be made from any crystal form.

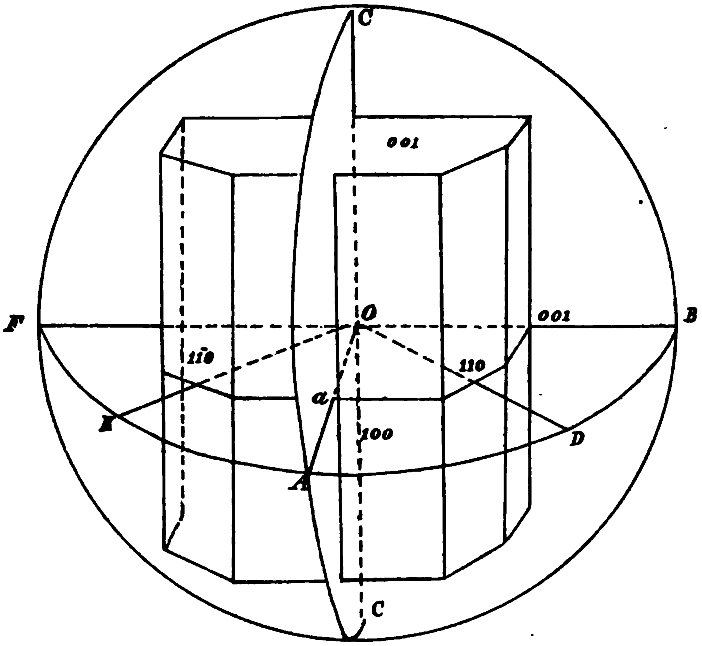

Fig. 15. Spherical Projection.

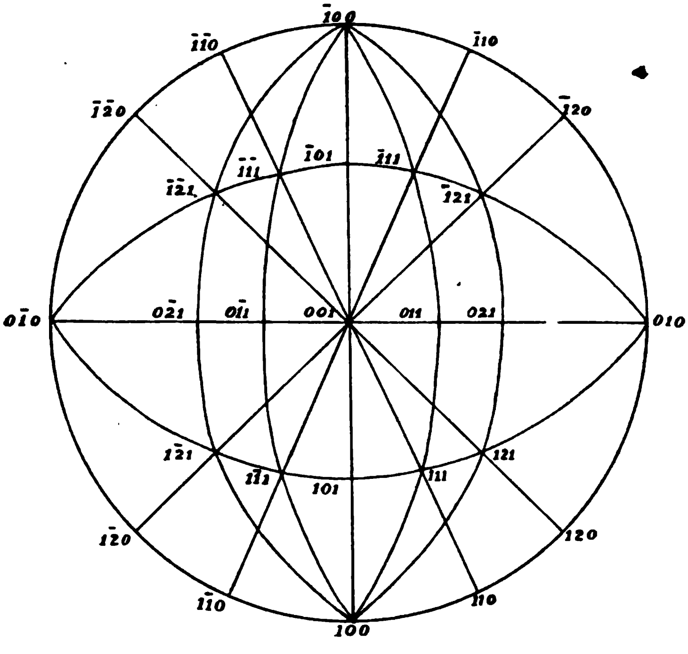

Fig. 16. Stereographic Projection.

STEREOGRAPHIC PROJECTION: If the hemisphere of spherical projection be subjected to a second projection on to a horizontal plane, and the eye be placed at the lower end of the diameter normal to this plane, the great circles appear either as arcs of circles or as straight lines.

If the orthorhombic form seen in figure 12 be represented in stereographic projection, it would appear as in fig. 16. In this representation the upper half of the form is supposed to be above the eye of the observer who looks toward the zenith. The poles of the various planes thus visible would be as represented, the conventional position of all the planes and their symbols being preserved.

For all forms with rectangular axes the pole of the basal plane will be at the center of the horizontal representation, and those of the pinacoids will be at the extremities of the principal diameters.

The poles of pyramids and domes are within their respective great circles, according to their axial intercepts.

Stereographic projection has been used extensively by Michel Lévy to represent graphically the optical characters of minerals, especially the feldspars, in polarized light.

A ZONE is a series of planes parallel to the same line though not parallel to each other. It is a term derived from spherical projection. All the vertical planes represented in figure 15, for instance, having their poles in the same great circle, constitute a *zone*. The line through the center of the crystal, to which they are all parallel, is the *zone-axis*.

## THE SIX CRYSTALLOGRAPHIC SYSTEMS.

It has been said already that all crystalline substances are divisible into classes, *isotropic* and *anisotropic*. In the isotropic class are the substances that crystallize in the cubic or *isometric* system. In the anisotropic class are the crystals of the other five systems.

THE ISOMETRIC SYSTEM: The crystals of this system play but a very insignificant part in practical microscopic petrography. This is because they are very rare as rock-forming minerals, and also because they are usually identifiable by the simplest tests.

The axes are all equal and at right angles, hence they are all expressed by unity, and any one of them may be taken for the vertical axis. Three principal planes of symmetry* define the position of the crystallographic axes. Six secondary planes of symmetry bisect the angles between the principal planes. A great variety of holohedral and hemihedral forms have been described, but they are comparatively unimportant to the petrographer, Those of most importance microscopically are the cube, octahedron, dodecahedron, and trapezohedron.

The cube, figure 17, is a six-sided solid, each of whose faces is parallel to two axes and cuts the other one. Sections are often squares. The octahedron (fig. 18) is an eight-sided solid, each of whose planes cuts all three axes at equal distances. It is a double equilateral pyramid. Sections are often rhombs. The dodecahedron (fig. 19) is a twelve-faced solid, each of whose planes is parallel to one axis and cuts the other two at equal distances. Sections are often hexagons. The trapezohedron (fig. 20) is a form of twenty-four similar faces each of which cuts one axis at unit length, and the other two at some multiple of that unit length. Each face is a trapezium. Sections are often octagons. This form is so common in leucite that it is sometimes called a leucitohedron.

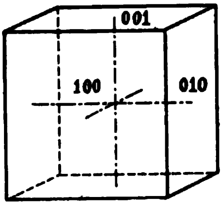

**Fig. 17. Cube.**

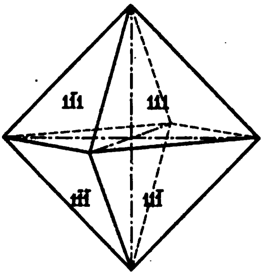

**Fig. 18. Octahedron.**

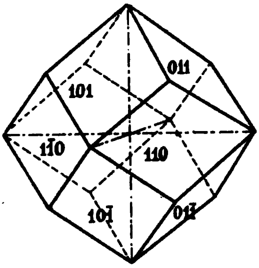

**Fig. 19. Rhombic Dodecahedron.**

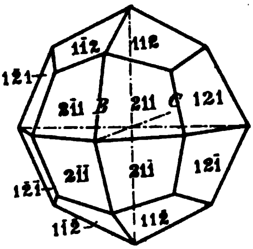

**Fig. 20. Trapezohedron.**

THE TETRAGONAL SYSTEM has three crystallographic axes at right angles to each other. The two lateral axes are equal, and the vertical axis is either longer or shorter.

It has one principal plane of symmetry, parallel to the base, and four secondary planes which are perpendicular to the base and stand at angles of 45° with each other, two of which contain the lateral axes.

---

* The symmetry described throughout this chapter is that of the normal group of each system; that is, the highest grade of symmetry found in the system.

The vertical axis $c$ is obtained from the equation

$$\tan 001 \wedge 101 = c, \text{ for a dome,}$$

or

$$\tan 001 \wedge 111 . \tfrac{1}{2}\sqrt{2} = c, \text{ for a pyramid,}$$

which are easily understood from an examination of figures 12 and 16.* The axial ratio (p. 20), or the ratio existing between the unit lengths of the two unequal axes $a$ (or $b$) and $c$ is an important element, since it is the fundamental expression for the inclination of the planes of the crystal on its axes. It is a

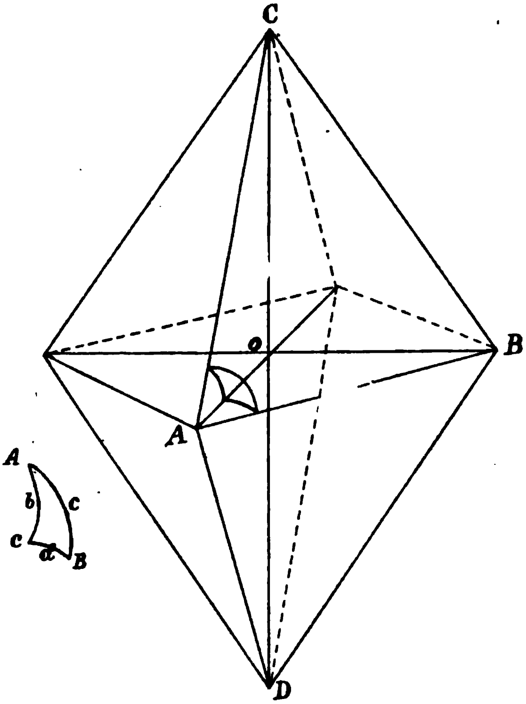

**Fig. 22. Fundamental Form of the Tetragonal System.**

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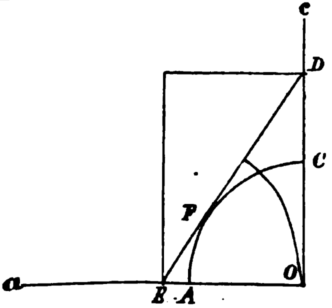

**Fig. 21. Value of the Vertical Axis.**

*Thus: Let the angle $A\ O\ C$ be the right angle at the centre of the crystal formed by the intersection of the axes $a$ and $c$. Let $E\ D$ be a dome face, 101, tangent on the spherical projection at $F$. The angle $D\ E\ O$ is the supplement of the angle $001 \wedge 101$. If $a$ be represented by $E\ O$ $c$ will be $D\ O$. Form a circle with $E$ as centre and $E\ O$ as radius, then will $D\ O$ (or $c$) be its tangent. Hence $c = \tan 001 \wedge 101$.

constant quantity, for the same substance, and serves to identify minerals in the same manner as specific gravity or light phenomena.

$$\text{Since } c = \tan 001 \wedge 101$$
$$\text{and } a = \tan 101 \wedge 001$$

and $c$ is not equal to $a$, it is evident not only that the angles $001 \wedge 101$ and $101 \wedge 001$ are supplements of each other, but also that it is necessary to ascertain by measurement the value of one of the interfacial angles. If $a$ be unity and $101 \wedge 001$ be known and represented as $p$, the axial ratio becomes $1 : \dfrac{\tan 001 \wedge 101}{p}$

Employing the pyramidal faces of the fundamental form (figure 22) we have, $a$ being assumed equal to unity,

$$c = \tan 001 \wedge 111 \times \tfrac{1}{2}\sqrt{2}$$

If, in figure 12, considered as tetragonal, the planes $111$, $\bar{1}11$, $\bar{1}\bar{1}1$, $1\bar{1}1$, $\bar{1}\bar{1}\bar{1}$, $1\bar{1}\bar{1}$, $11\bar{1}$, and $\bar{1}1\bar{1}$ be developed at the expense of all the others, the resulting solid would be the fundamental form of the tetragonal system (p. 27) shown in figure 22, in which the lateral axes are equal, and the vertical axis greater. Its stereographic

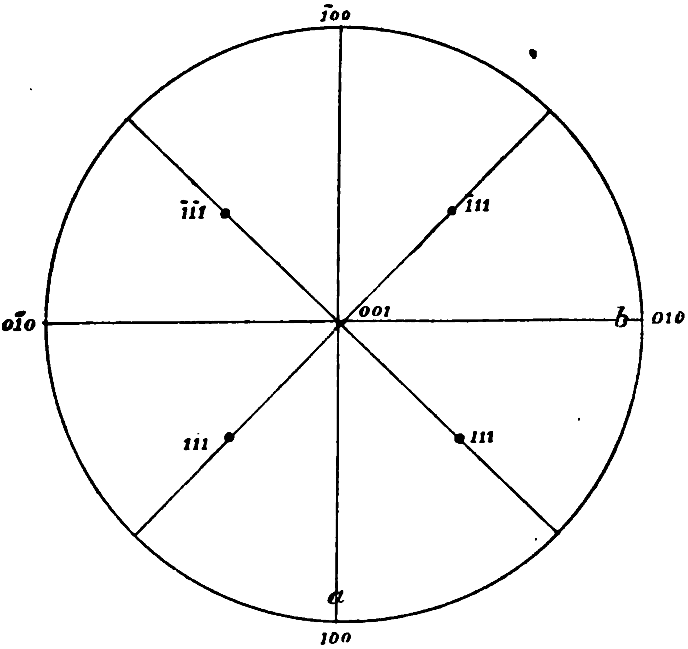

Fig. 23. Stereographic Projection of the Fundamental Form of the Tetragonal System.

projection is seen in figure 23. The pinacoids and the prisms are obliterated.

The important forms of the tetragonal system include the base, prisms and pyramids. The base is a pinacoid parallel with the lateral axes. The other terms have been previously defined. These forms commonly appear in various combinations, illustrated in figures 24, 25, and 26. The first is a combination of the prism and the pyramid, seen in zircon. The second is a prism terminated by a pyramid and a base, as found in vesuvianite. The third is a combination of two prismatic forms and two pyramidal forms, occurring in rutile.

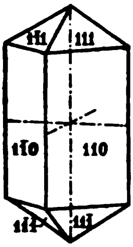

Fig. 24. Combination of the Tetragonal Prism and the Pyramid, Zircon.

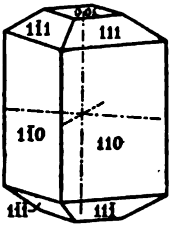

Fig. 25. Combination of the Tetragonal Prism and the Pyramid and Base, Vesuvianite.

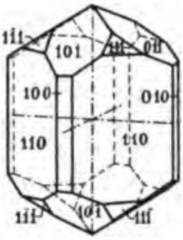

Fig. 26. Combination of the Prism with Two Pyramids, Rutile.

THE HEXAGONAL SYSTEM: This system has three equai axes perpendicular to a vertical axis. (fig. 27). The horizontal axes are inclined to each other at angles of 60°. The vertical axis is either longer or shorter. The hexagonal system is divisible into:

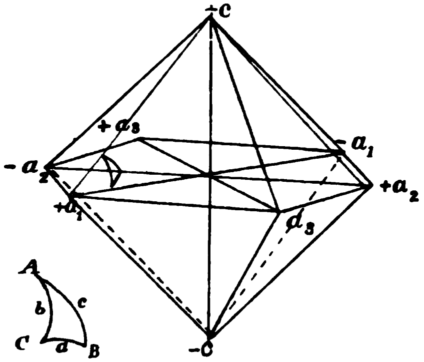

Fig. 27. Axes of the Hexagonal System.

HEXAGONAL DIVISION, which has six secondary planes of symmetry, vertical and perpendicular to the principal plane of symmetry. The secondary planes meet at angles of 30° in the vertical axis and three of them contain the lateral axes; and

RHOMBOHEDRAL DIVISION, which may strictly be considered as embracing half-forms of the hexagonal division. This has three secondary planes of symmetry which stand at 60° with each other, and mutually intersect in the vertical axis; and no principal plane of symmetry.

The lateral axes for both divisions are represented by $a_1$, $a_2$, $a_3$, as in figure 27, and the vertical axis by $c$.

THE FUNDAMENTAL FORM is a hexagonal pyramid, bounded by planes which intersect the vertical and two contiguous lateral axes at their unit lengths and are parallel respectively to the other lateral axes. It has twelve sides whose indices are as follows:

$$10\bar{1}1,\ 01\bar{1}1,\ \bar{1}101,\ \bar{1}011,\ 0\bar{1}11,\ 1\bar{1}01$$
$$10\bar{1}\bar{1},\ 01\bar{1}\bar{1},\ \bar{1}10\bar{1},\ \bar{1}01\bar{1},\ 0\bar{1}1\bar{1},\ 1\bar{1}0\bar{1}$$

For this system the tangent principle is expressed by

$\tan 0001 \wedge 1122 = c$, obtained from the unit diagonal pyramid; or

$\tan 0001 \wedge 1011 \times \frac{1}{2}\sqrt{3} = c$, obtained from the unit pyramid.

For a hexagonal pyramid (figure 27)

$$\tan \tfrac{1}{2}\ 10\bar{1}1 \wedge 01\bar{1}1 = \sin c \sqrt{\tfrac{1}{3}}$$

For computing the axial ratio any hexagonal pyramid may be chosen, since in all forms of the same substance the ratios of the axial intercepts are the same.

The value of the axis $c$ in terms of $a$ is expressed by,

$$c = \tan\ (\text{angle})\ b;\ \tan b = \tan B \sqrt{\tfrac{3}{4}}$$

or

$$\sin b = \cot A \sqrt{3},\ (\text{fig. } 27)$$

where $B$ is one-half the basal edge of the pyramid and $A$ is one-half of its polar edge. (Williams).

The process is analogous to that of the tetragonal system. It is only necessary to note that the side $a$ of the spherical triangle is 60° instead of 45°.

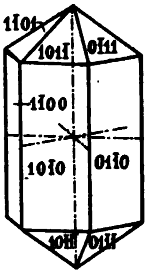

Fig. 28.

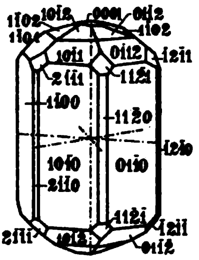

Fig. 29.

Combinations of Hexagonal Prism and Pyramids, Apatite.

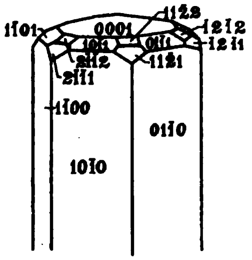

Fig. 30.

Combination of Hexagonal Prism, Base and Pyramids, Beryl.

The important forms of the hexagonal division are the base and the hexagonal prisms and pyramids. They commonly occur in various combinations, as shown, for example, in figures 28, 29, and 30. The first two show forms assumed by apatite, while the last is seen in beryl. In the rhombohedral division, the common crystals are strikingly different from the preceding. They are illustrated by figures 31, 32, 33, 34, 35, and 36. The characteristic forms here are the rhombohedron and the scalenohedron. The former, figures 31 and 32, is a six-sided solid, each of whose faces is a rhomb. It has six like lateral edges forming a zigzag line around the crystal, and six like terminal edges, three above and three below. It may be derived from the double hexagonal pyramid by extending alternate faces until those between disappear, therefore any face of the rhombohedron has the same relation to the axes as any face of the hexagonal pyramid; that is, it cuts two lateral axes at equal distances and is parallel to the third; it also cuts the vertical axis. The scalenohedron, figure 31, is a twelve-sided solid each of whose faces is a scalene

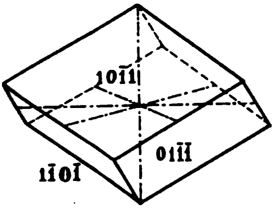

Fig. 31.
Rhombohedron of Calcite, by Cleavage.

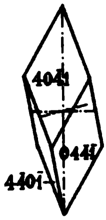

Fig. 32.
Rhombohedron of Calcite.

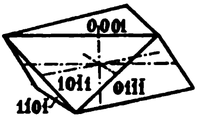

Fig. 33.
Combination of Rhombohedron and Base, Hematite.

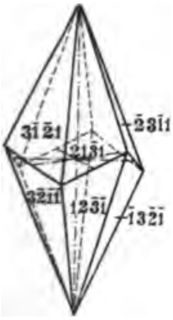

Fig. 34.
Scalenohedron, Calcite.

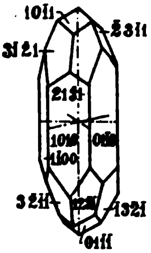

Fig. 35.
Combination of Prism, Scalenohedron and Rhombohedron, Calcite.

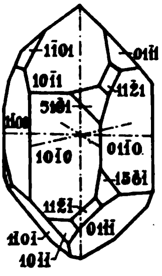

Fig. 36.
Combination of Prism and Rhombohedron, modified by the right trigonal Pyramid, and the right plus trapezohedron. Right-handed Quartz.

triangle. Its lateral edges form a zigzag around the crystal like that around the rhombohedron, but the terminal edges are not all alike—alternate terminal edges are alike, but unlike those between. It may be derived from the double dihexagonal pyramid by extending alternate faces to obliterate those between. The forms shown in figures 31, 32, 33, 34, and 35, are found in calcite; figure 36 is a crystal habit assumed by quartz, which is characterized by the faces of a trigonal trapezohedron. This leads to a lower grade of symmetry than that of calcite. This trapezohedron may be derived by extending the alternate faces of a scalenohedron until those between disappear. Each face, therefore, has the same relations to the axes as each face of the scalenohedron (and also the double dihexagonal pyramid); that is, it cuts all three lateral axes in such a way as to have a ratio on any two adjacent between 1:1 and 1:2; it also cuts the vertical axis. The trigonal trapezohedron is not known to occur alone, although it is a closed form.

The Orthorhombic System has no principal plane of symmetry, but three secondary planes.

There are three unequal axes, at right angles to each other, lying in the secondary planes of symmetry. Figures 37 and 38 illustrate the positions of the axes and their nomenclature. The axis *b* is the greater of the lateral axes, as is indicated by a horizontal line (macron) above it; *a* is the shorter, marked by a corresponding symbol (brève), and *c*, the vertical axis, is designated by a perpendicular line above it. They are plus or minus as in the tetragonal system, *b* is known as the macrodiagonal axis and in calculating the axial ratio is taken as unity and *a* as the brachydiagonal. The pinacoidal sides to which they are respectively

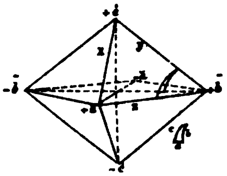

**Fig. 37.**
**Axes in the Orthorhombic System, Pyramidal Form.**

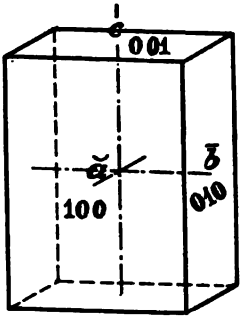

**Fig. 38.**
**Simple Orthorhombic Form.**

parallel are hence named *macropinacoid* and *brachypinacoid.* There being three axial values, there are two axial ratios,

$$\frac{a}{b} \text{ and } \frac{c}{b}$$

From the spherical triangle $a\ b\ c$ (see fig. 37)

$$\text{Cos angle } a = \frac{\cos \frac{1}{2}\text{Y}}{\sin \frac{1}{2}\text{Z}};\ \text{tg. angle } a = a$$

$$\text{Cos angle } b = \frac{\cos \frac{1}{2}\text{Z}}{\sin \frac{1}{2}\text{Y}};\ \text{tg. angle } b = c$$

These values may be computed from the angles measured, by the use of spherical triangles, on the stereographic projection, and by the aid of the tangent principle.

The axes are related to the angles as expressed by the following equations:

$$\tan(100 \wedge 110) = a,$$
$$\tan(001 \wedge 011) = c \text{ and}$$
$$\tan(001 \wedge 101) = \frac{c}{a}.$$

To place the orthorhombic crystal in conventional position any axis is made vertical and the longer lateral axis is turned so as to extend right and left.

The important forms of this system include the three pinacoids (basal, macro- and brachy-), already defined, and the prisms, pyramids and domes. The unit prism is the form each of whose four faces is parallel to the vertical axis and cuts the lateral axes at unit distances on those axes. Each face of a macroprism cuts the macroaxis ($b$) at a multiple of unit distance, while the faces of a brachyprism cut the brachyaxis at a multiple of unit distance. The pyramids are similarly classified as unit pyramids, macropyramids and brachypyramids. The macrodome is parallel to the macroaxis and cuts the other two axes: the brachydome is parallel to the brachyaxis and cuts the other two.

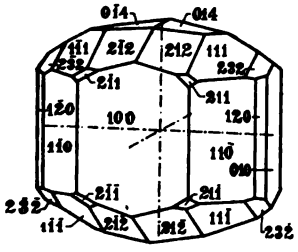

Fig. 39.
Combinations seen in Hyperthene.

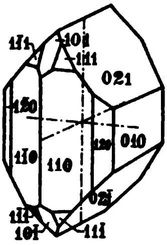

Fig. 40.
Combinations seen in Olivine.

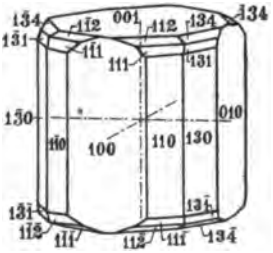

Fig. 41.
Combinations seen in Cordierite.

These forms nearly always occur in combinations. Thus, figure 39 shows a combination of the macropinacoid 100, brachypinacoid 010, unit prism 110, brachyprism 120, unit pyramid 111, brachypyramid 232, two macropyramids 212 and 211 and the brachydome 014, as found in hypersthene. Figure 40 is a combination occurring in olivine; figure 41 illustrates a habit of cordierite, and figures 42 and 43 are drawings of crystals of barite.

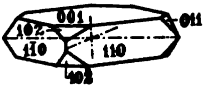

Fig. 42.
Form of Barite.

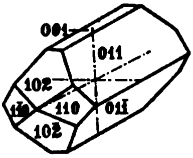

Fig. 43.
Form of Barite.

THE MONOCLINIC SYSTEM has one secondary plane of symmetry; viz, that which includes the vertical axis *c* and the clinodiagonal axis *a*. Its three axes are unequal, and *b* is perpendicular to the others, and hence to the plane of symmetry. That face which is parallel to the inclined axis *a* and the vertical axis is the

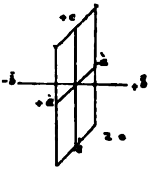

Fig. 44.
Pinacoids and Axes of the
Monoclinic System.

*clinopinacoid*, the axis *a* being the *clinodiagonal*. Similarly the *orthopinacoid* is parallel to the *orthodiagonal axis b* and to the vertical axis. See figure 44 in which these parts and relations are illustrated. In stating the axial ratio *b* is taken as unity. The angle between *a* and *c* is expressed by $\beta$.

For the axial ratio:

$$a = \frac{\tan 100 \wedge 110}{\sin \beta}; \; c = \frac{\tan 001 \wedge 011}{\sin \beta}$$

$$\frac{c}{a} = \frac{\sin 001 \wedge 101}{\sin 100 \wedge 101}$$

To place a monoclinic crystal in conventional position the axis which is perpendicular to the plane of the other two must be made to extend right and left; of the other two the shorter is usually the axis *a*, and is placed so as to extend downward to the front, while the other axis is vertical.

The important forms of the system resemble those of the orthorhombic system, but the system has less symmetry than the latter and therefore some forms are made up of a smaller number of faces. Further, the macro- forms of the orthorhombic system correspond to ortho- forms in the monoclinic system, and brachy- forms correspond to clino-. Thus, the orthodome consists of only two faces, both parallel to the orthoaxis and cutting the other two. The pyramid has only four faces and consists of two pairs of parallel planes; it is not a closed form. Figure 45 shows a crystal of augite, the forms present being the orthopinacoid 100, clinopinacoid 010, unit prism 110, and unit pyramid $\bar{1}11$. Figure 46 illustrates a habit of orthoclase with the base 001 and the clinopinacoid 010 combined with the unit prism 110, the clinoprism 130, the unit pyramid $\bar{1}11$, and the orthodome $\bar{2}01$. Figure 47 is a common habit of epidote; its forms are the base 001, orthopinacoid 100, orthodome $\bar{1}01$, and unit pyramid $\bar{1}11$.

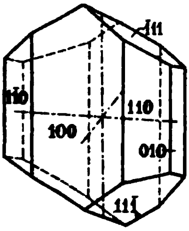

Fig. 45.
Crystal of Augite.

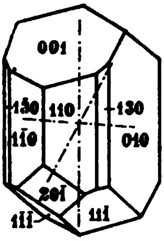

Fig. 46.
Crystal of Orthoclase.

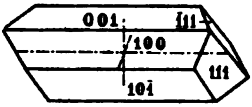

Fig. 47.
Common Habit of Epidote; combination of base, orthopinacoid, orthodome and unit pyramid.

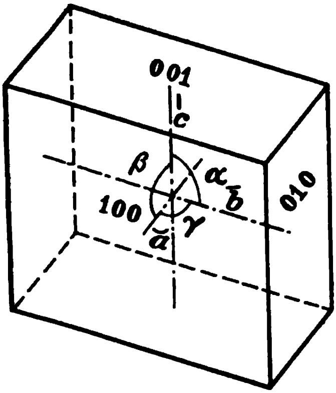

Fig. 48.
Simple triclinic form, or diametral prism.
Conventional position of the axes.

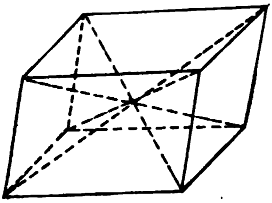

Fig. 49.
Simple Triclinic Form, crystal axes not shown.

**The Triclinic System** has no plane of symmetry. All its forms, in the technical sense of that term, consist of only two parallel planes, which necessarily can occur only in combination with other forms. Its three axes are all unequal and oblique to each other at their point of intersection. They are lettered *a*, the *brachydiagonal, b* the *macrodiagonal* and *c,* the *vertical.* The *brachypinacoid* is parallel to *c* and *a,* and the *macrodiagonal* is parallel to *c* and *b.* See figure 48 for an illustration of the conventional position of these axes, and figure 49 for a simple triclinic form in which the only element of symmetry is the point at the centre.

In the use of spherical projection it has to be noted that the spherical angles of the triangle 100, 010, 001, are the supplements of the axial angles; viz: The angle at $100 = 180^\circ - \alpha$; that at $010 = 180^\circ - \beta$; and that at $001 = 180^\circ - \gamma$. They can be computed from the angles $100 \wedge 001$, $100 \wedge 010$ and $001 \wedge 010$ of the same triangle.

The axial ratios are expressed thus, *b* being unity:

$$\frac{c}{b} = \frac{\sin 001 \wedge 100}{\sin 100 \wedge 010}$$

$$\frac{a}{b} = \frac{\sin 100 \wedge 111}{\sin 100 \wedge 110}$$

To place a triclinic crystal in conventional position any axis is made the vertical; of the other two the longer is usually the axis *b* which must extend right and left and incline downward to the right; at the same time the axis *a* must incline downward to the front.

The important forms of the system are named like those of the orthorhombic system, but in this case the lack of planes and axes of symmetry reduces the number of faces in any form to two, which are always opposite and parallel. Figure 50 repre-

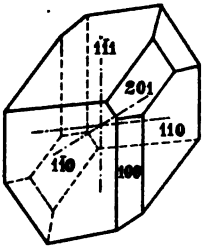

Fig. 50.
Triclinic form of Axinite, showing Two Unit Prisms, Macropinacoid, Macrodome and two Unit Pyramids.

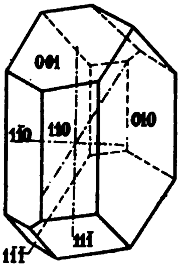

Fig. 51.
Combinations shown in Albite.

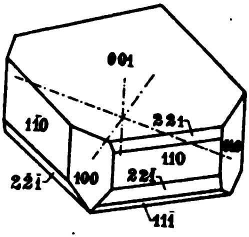

Fig. 52.
Triclinic Crystal of Rhodonite.

sents a crystal of axinite which shows the two unit prisms 110 and 1$\bar{1}$0, macropinacoid 100, macrodome 201, and two unit pyramids 111 and 1$\bar{1}$1. Figure 51 is a combination of the base 001, brachypinacoid 010, two unit prisms 110 and 1$\bar{1}$0, unit pyramid 1$\bar{1}$1, and macropyramid $\bar{2}$11, occuring in albite. Figure 52 is another illustration of triclinic crystals; it is a habit of rhodonite.

Minerals of the monoclinic system, and also more especially, those of the triclinic system, possess the highest interest and importance in microscopic petrography. This is because of their great preponderance in the constitution of the crystalline rocks, and the great variety of aspects which they present in polarized light. These facts have led to the discovery of delicate methods of examination, and to the multiplication of accurate instruments.

## IMPORTANT PHYSICAL CHARACTERS OF MINERALS.

*Twinning* is a very common phenomenon in minerals examined microscopically. In general, a twinned crystal has one of its halves in reverse position with respect to the other, having been turned, as it were, 180° out of its normal position, about an assumed axis, or *twinning axis*. The composition face of the two parts is usually the twinning plane, but it may be some other plane. The fine lines, or striations, seen on the triclinic feldspars, are produced by *polysynthetic twinning*. (See further, on twinning, under Application of Polarized Light, Chapter III).

*Cleavage* is the tendency of minerals to separate naturally along planes parallel to some natural or possible crystal faces, producing more or less smooth surfaces. This tendency usually exists in more than one direction, and is more marked in some directions than in others. After polarization of light it is to the petrographer one of the most important of the physical characters of minerals, as it frequently furnishes the only means by which the directions of faces and axes can be known. It should be distinguished carefully from

*Parting,* which is generally a secondary feature superinduced on minerals by pressure or incipient decay, or by twinning, and in which the laminae are generally coarser and more irregular than in genuine cleavage. In parting the laminae may be a millimetre or more in thickness; in cleavage usually less than a twentieth of a millimetre.

*Specific Gravity* is the relative weight of a mineral compared to water, and is used not only for the identification of a mineral, but also for the separation of minerals of any desired specific gravity from a mixed powder. Several liquids are known heavier than the common rock-forming minerals. When the powder floats the liquid is diluted gradually by a lighter liquid.

THOULET'S SOLUTION.* Potassium-mercuric iodide; sp. gr. commonly 3.01—3.1; max. density, 3.196; $KI : Hg\ I_2 = 1 : 1.24$; color yellowish-green, becoming reddish from separation of iodine; dilution by water; density changes slowly by exposure to air through absorption of water.

So long as the proportion of the two salts $KI$ and $Hg\ I_2$ remains the same, water may be added even to reduce the specific gravity to 1.0, and by evaporation on a water-bath the highest specific gravity may be restored. If by use or otherwise the proportion between the salts become changed, with an excess of $Hg\ I_2$ a yellow hydrous double-salt in acicular crystals is observable; with excess of $KI$ this substance appears in cubes. The green color may be restored, as well as the original composition, by adding metallic mercury during a slow evaporation on the water-bath. Metallic iron decomposes this liquid, which is very corrosive and deadly.

KLEIN'S SOLUTION. Cadmium borotungstate + water; sp. gr. 3.36; max. density 3.365; color, light yellow; dilution by water. spoiled by contact with zinc, iron, lead or with carbonates.

At high specific gravity this liquid is so oily that it cannot be used. It is poisonous but less corrosive than Thoulet's solution.

BRAUN'S SOLUTION. Methylene iodide, $CH_2\ I_2$: sp. gr., (at 16° $C$.) 3.3243, varying about 0.0022 for each degree ($C$.) of change of temperature; color yellow, becoming reddish; dilution by benzole or ether; spoiled by water or alcohol; not injured by contact with metallic substances; after dilution may be reconcentrated by evaporation; does not decompose on exposure to air, its yellow color may be restored by shaking it up in a bottle in which is a little metallic mercury.

Braun's solution is the most generally useful, owing to the stability of its composition, its mobility and its high index of refraction (1.74092 at 16° C.) which renders it useful for determining indices of refraction by total reflection. It is also useful as an immersion liquid on the objective of the microscope, and over the condenser below the stage.

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* Also known as Sonstadt's solution, from E. Sonstadt who first used it extensively.

THE WESTPHAL BALANCE. This instrument is indispensable. It is represented by figure 53. Its purpose, as generally used, is to ascertain the specific gravity of a liquid in which have been placed one or more mineral grains the density of which is the same as that of the liquid, and which, therefore, swim at random in the body of the liquid. The liquid is brought to the density of the mineral fragments by successive small additions of the concentrated liquid or of benzole, or ether (if the liquid be methylene iodide) according as it is already too light or too heavy. When the fragments are correctly adjusted to the liquid the specific gravity of the liquid is ascertained by causing the index of the bar to stand at the zero point of the scale. This is done by hanging the small weights which accompany the instrument on the long arm of the bar after the sinker is immersed in the liquid and hung from the hook at the longer end of the bar. These weights are so graduated that they severally indicate, after the bar is balanced, the integer and

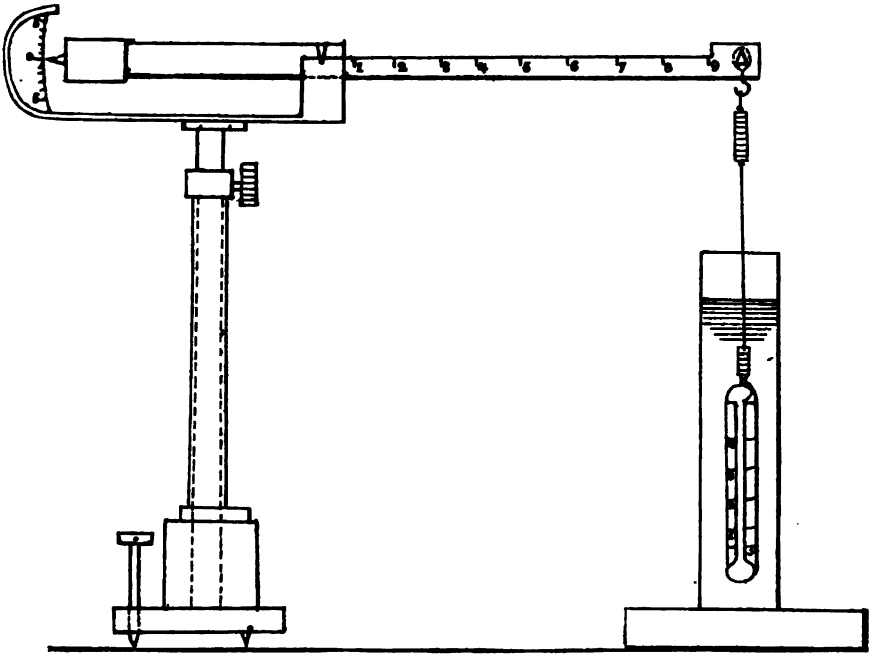

**Fig.53. Westphal Balance.**

decimal figures of the number expressing the specific gravity. For example, the largest weights, when suspended from the hook on which the sinker is hung, each indicates one unit; when two such are necessary the integer of the specific gravity is 2.* The same rider, if put on the bar at the figure 6, gives the tenths figure of the decimal, and the next smaller rider, if placed half-way between 1 and 2 on the bar, indicates .01½ or .015. The smallest rider when used is to be read in thousandths. These figures, when combined in succession, give 2.615 as the specific gravity of the liquid, and hence that also of the properly adjusted mineral fragments.

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* The weights are not in all cases made to differ as above, but a single large weight may contain the same as two or three of the large ones, and would therefore indicate the integer 2 or 3; and other integer weights are then to be used as riders, indicating tenths.

# CHAPTER III.

# APPLICATION OF POLARIZED LIGHT TO CRYSTALLINE SUBSTANCES.

The substances with which microscopic petrography has to do are divisible; first, as already stated, into *isotropic* and *anisotropic*. The anisotropic are again to be divided into *uniaxial* and *biaxial*, thus: *Uniaxial Minerals* include those of the tetragonal and hexagonal systems, having one optic axis (p. 26).

*Biaxial Minerals* include those of the orthorhombic, monoclinic and triclinic systems, having two optic axes (p. 32).

It is necessary to ascertain the peculiarities of the minerals of each of the crystallographic systems as they are manifested in polarized light. For this it will be well that the beginner now take note of the instrument which is known as the

Polarizing Microscope, illustrated by figure 54. It is that of Nachet, Paris. In addition to the parts usual to a common microscope, this instrument has the following:

1. *Two nicol prisms, A* and *T*, as already stated, (p. 15). For some special examinations a third nicol capable of horizontal rotation is mounted separately, to be placed over the ocular. The nicol *A* in this microscope is not revolvable, but is lifted easily from its place when not wanted (*A'*). The polarizer (nicol *T*), is revolvable on its axis. In ordinary work it stands constantly with its principal section (*i. e.* its shorter diameter) at right angles with the principal section of the upper nicol. This position should be such that when thus crossed the principal sections of the nicols stand true with the microscope; one nicol (analyzer) being right and left, and the other (the polarizer) front and rear. The lower nicol can also be raised and lowered readily without disturbing its centering, and can be swung away entirely, on a hinge (*T'*). When a thin section is examined over the lower nicol, or between the two nicols without the convergent lens described below, it is said to be done in *parallel polarized light*.

2. *Lens for convergent polarized light.* When the examination requires *convergent polarized light,* the lower nicol is covered with one or more powerful convergent lenses, which are supported on a special brass casting and can be readily thrown out from the axis of the microscope when not in use. By means

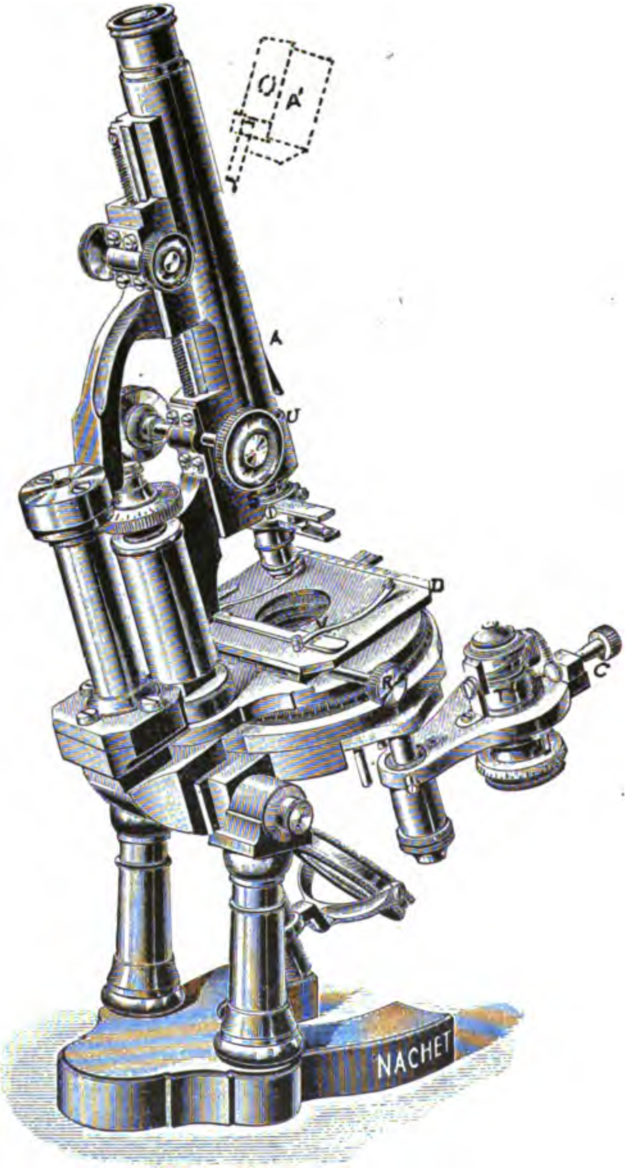

**Fig. 54. Polarizing Microscope of Nachet.**

of the ratchet (*C*) both the convergent lens and the lower nicol can be lowered or raised till the upper surface of the lens is

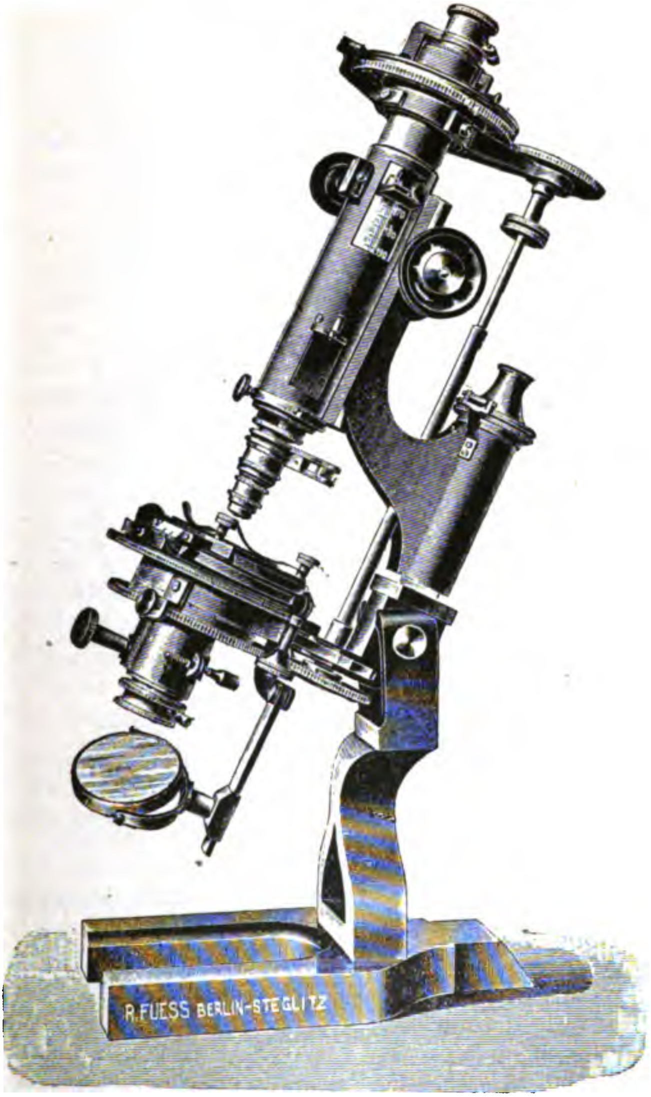

**Fig. 54a. The Fuess Microscope.**

nearly or quite in contact with the glass slide holding the thin section under examination.

3. *Rotation of the stage.* The stage rotates about the axis of the microscope, carrying with it also the objective. Thus

the centering of the object, under examination, is not disturbed; and it can be brought accurately into any angular position with respect to the vibrations of light in the nicol prisms. (see p. 47). The rim of the rotating stage has a scale, and a vernier, by which the amount of rotation can be accurately determined.

4. *Cross hairs are placed in the ocular*, one running right and left and the other front and rear, precisely at right angles, and in agreement with the principal sections of the nicols when crossed.

The objectives used for the most work are Nos. 3 and 7; the former for searching out an object and for making the preliminary examination, and the latter for convergent light and high power.

The foregoing are the essential parts of the petrographical microscope, so far as it differs from a common microscope. For the purpose of accurate reading or registration of the phenomena, or for special methods of operation, other appliances have been devised. These appertain principally to the use of convergent polarized light. They are explained and illustrated in the following pages in connection with the application of polarized light to the minerals of the different crystallographic systems.

In use, the stage of the microscope is supposed to be divided into quadrants N E., S W., and NW., S E., in the manner of a geographical map.

As a representative of other microscopes adapted for accurate work in optical mineralogy that of Fuess is illustrated on page 43.

That of Leiss is preferred especially for students' use. The American microscope of Bausch and Lomb is also adapted to students' use.

*Laboratory illustrations*: The student should study the petrographical microscope, becoming familiar with the characteristic parts and its appliances; the lower nicol, the upper nicol, objectives, oculars with cross-hairs and with micrometer, the condenser, the fine adjustment. Determine the amount which one revolution of the fine adjustment screw raises the objective. Measure the thickness of a piece of glass by focusing carefully on the lower edge and then on the upper edge. Measure the same with the eye-piece micrometer. For this purpose a fragment may be set on edge slightly imbedded in wax or paraffin.

## THE ISOMETRIC SYSTEM AND POLARIZED LIGHT.

Perhaps the most important of the minerals of the isometric system which appear as constituents of rocks, are magnetite and pyrite, and these are opaque, and hence must be examined in other ways than by polarized light. Others, such as garnet, spinel, fluorite, leucite, sodalite are transparent, but not of frequent occurrence.

As has been stated, they are *isotropic,* i.e., they are dark in thin section, between crossed nicols, and remain dark during an entire rotation of the stage carrying them into every angular position with respect to the vibrations transmitted from the lower nicol. This is true in whatever direction the thin section may be cut. They have no interference figure (p. 50) in convergent light, and no interference colors in parallel polarized light.*

Other isotropic substances can be distinguished from those of the isometric system by their forms or by the absence of cleavage traces.

An anisotropic crystal cut perpendicular to an optic axis (p. 46) might be mistaken for an isotropic crystal. Care must be taken, therefore, should there be any doubt, to make a trial for the interference figure (p. 50) in convergent light.

*Laboratory illustrations.* The student may examine thin sections of garnet, fluorite or leucite. The most common rock-forming minerals of the isometric system are magnetite and pyrite, which being opaque, can be examined microscopically only by light reflected from their upper surfaces.

## UNIAXIAL MINERALS.

### THE TETRAGONAL SYSTEM AND POLARIZED LIGHT.

This system includes the first section of uniaxial minerals, of which the hexagonal system constitutes the other section. They are called uniaxial because, although they are doubly refracting (p. 15) such minerals have one direction in which, when viewed in thin sections between crossed nicols, they appear as isotropic substances. This direction is called the *optic axis,* or the *principal axis,* sometimes the *primary axis.*

### THE HEXAGONAL SYSTEM AND POLARIZED LIGHT.

Minerals of the hexagonal system have the same phenomena in polarized light as those of the tetragonal system, and must be distinguished from them by their cleavage or other physical characters. Of the uniaxial minerals the hexagonal are more numerous and important than the tetragonal.

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* Some crystals in the isometric system when under strain are not isotropic.

The term Optic Axis plays an important rôle in microscopic petrography, and as it will be of frequent occurrence in connection with the discussion of the other crystallographic systems, it will be necessary at the outset to have definite and correct ideas concerning it. It should not, as a term, be confounded with *axis of ether vibration* (p. 53), nor with *crystallographic axis,* although they sometimes coincide. Its discussion involves several optic phenomena common to all anisotropic media and serves as an introduction to the real problems of petrography.

The student must keep in mind the principles of polarization of light as given in Chapter II.

The physical molecules of a uniaxial crystal are arranged symmetrically about the vertical axis *c;* when a ray of light from the lower nicol, having its vibrations in one direction, enters a thin section of a uniaxial crystal perpendicular to its surface in the direction of its vertical axis *c,* it is not disturbed, because round about the vertical axis vibrations can take place with equal ease in all directions perpendicular to it. Such a polarized extraordinary ray (p. 13), therefore is only intercepted by the upper nicol so as to produce darkness as in an isotropic body. Hence, in *uniaxial crystals* the *axis c coincides with the optic axis.*

If a ray from the lower nicol enter perpendicularly a thin section of a uniaxial crystal in any other direction than perpendicular or parallel with *c,* it is doubly refracted and polarized, except when the principal optic section of the mineral is parallel to that of either nicol, its two parts advancing in different directions with different rates, the extraordinary ray taking an oblique direction. These parts vibrate perpendicular to their directions of movement, and perpendicular to each other; one of them vibrates in a plane containing the incident ray and the optic axis, (called the *principal optic section*), and is distinguished as the *extraordinary ray.* The other vibrates perpendicular to this plane, and is known as the *ordinary ray.*

On emerging from the section the extrordinary ray is more or less advanced than the ordinary. The essential fact is, however, that on reaching the upper nicol and being reduced by it to a uniform direction, the vibrations of the two rays, not being equally advanced, interfere with each other, producing color.

The thin section therefore, appears colored with some of the tints of the solar spectrum, or with some of their combinations.

The ***kind*** of color thus produced depends on: (1) The mineral examined; (2) The thickness of the section and (3) The direction in which the section is cut with respect to the optic elements of the crystal. The ***amount,*** or ***intensity,*** of color depends on the angle between the principal optic section of the mineral and the principal section of either nicol, being greatest when it is 45°. This greatest intensity, or brilliancy occurs at four places in a complete revolution of the section.

The color is least when this angle is 0°; i.e., ***when the optic axis of the crystal lies in the principal section of either nicol, the light is extinguished and the section is nearly or quite dark.*** These points of darkness are called ***positions of extinction.***

On passing through a petrographical microscope light undergoes important changes. If it also pass through a mineral section on the stage it is doubly polarized three times. These changes are illustrated by the vertical section and plan seen in figure 55. After reflection from the mirror *M*, the ray of light enters the lower nicol *IJ*, where it is doubly refracted; the two resultant rays being completely polarized, one vibrating (the ordinary—*O*) in a plane normal to the principal optic section (p. 46), and the other (extraordinary—*E*) in the principal section. The *O* ray vibrates in the plane *AA′* of the plan, and the *E* ray in the plane *PP′*. The ordinary ray has such a high index refraction and strikes the balsam layer uniting the nicol at such an angle as to suffer total reflection, and it is absorbed at *W* by the black walls about the nicol; only the extraordinary ray passes through the nicol.

When this ray strikes an anisotropic mineral section as *SS′*, not cut parallel with any optic elements, at any position other than extinction (p. 49), it is again divided into two rays which may be called the ordinary (*O′*) and the extraordinary (*E′*) rays for this mineral. In the drawing the mineral is supposed to be uniaxial, and the *O* ray is not refracted since the incidence is normal. In biaxial crystals both rays would be refracted in the general case, since in such crystals both rays have the character of extraordinary rays. After entering the section *SS′* the two rays (*O′* and *E′*) are vibrating in planes at right angles to each other, one (*E′*) vibrating in the principal optic section of the mineral. Neither plane, however, is parallel to the plane of vibration of the ray as it left the lower nicol, since the section is

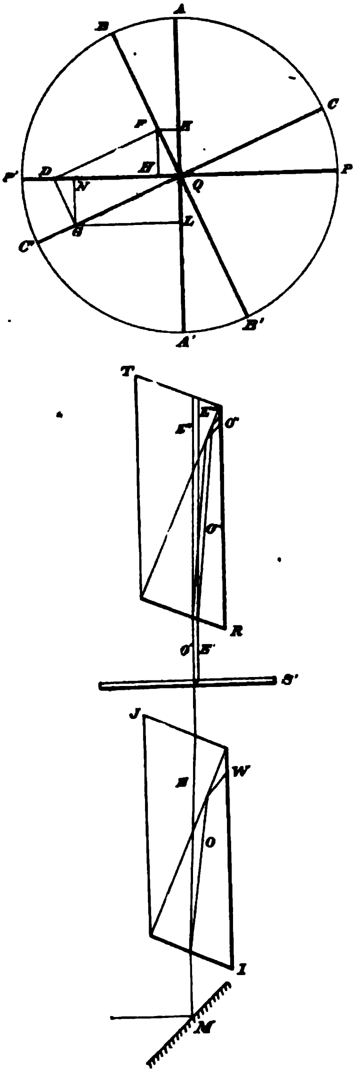

Fig. 55.
Changes of Light in Passing Through a Petrographical Microscope.

not at a position of extinction. Then in the plan, if $DQ$ represent the vibration of the ray after passing the polarizer it will be divided by the mineral section into two rays whose vibrations may be represented by $FQ$ and $GQ$, if the vibration planes of the mineral are in the positions $BB'$ and $CC'$. These two rays will pass upward to the analyzer $RT$ where a third division will produce two rays from each of them. If $GQ$ represent the vibration of the ordinary ray ($O'$) of the mineral, $HQ$ will be the vibration of the ordinary ray $O''$ produced from this by the upper nicol, and $KQ$ that of the extraordinary ray ($E''$). Further, the extraordinary ray ($E'$) of the mineral, whose vibration is $FQ$, will be divided in the upper nicol into an ordinary ray ($O'''$), whose vibration is represented by $NQ$, and an extraordinary ray ($E'''$), whose vibration is indicated by $LQ$. Now the two ordinary rays ($O''$ and $O'''$) will suffer total reflection in the upper nicol; therefore their vibrations $HQ$ and $NQ$ will disappear. But the two extraordinary rays ($E''$ and $E'''$), whose vibrations are represented by $KQ$ and $LQ$ will pass through the analyzer; and, since their vibrations are in the same plane, they will interfere, as they are derived from the same point source on the mirror and therefore have a fixed phase relation. This "interference" is nothing more than a combination of the two rays, and occurs whenever two rays have vibrations in the same plane and come from the same point source. In monochromatic light, this interterference will produce variation of intensity of the light, depending upon the difference of phase of the two rays. If the rays have no difference of phase, or a retardation of an integral number of wave-lengths, the interference will double the amplitude and quadruple the intensity. If the rays have a difference of phase of one-half wave-length, or any uneven multiple darkness will result. In ordinary white light, since the different colors constituting the light have different wave-lengths and are unequally refracted, interference will reduce the intensity of some colors, while increasing the intensity of others—therefore, interference will produce colors from white light. The color produced will depend upon the difference of phase, or the relative retardation, and this in turn depends upon the birefringence of the mineral concerned, upon the direction in which the section is cut with respect to the chief optical directions of the mineral, and upon the thickness of the section.

## DETERMINATION OF THE DIRECTION OF EXTINCTION.

This quality of alternate light and darkness is the most important and common phenomenon distinguishing anisotropic media from isotropic.

For accurately determining the positions of extinction, several methods have been devised. If the observer is forced to depend on the distinction of these positions by direct observation, he finds that it is impossible to make several readings exactly alike. The eye cannot distinguish small variations in the brightness of light. Sometimes numerous readings are made on the same extinction, and the average is taken.

*Calcite interference figure.* This method substitutes a distinction of form for a difference of light. A calcite plate cut at right angles to the optic axis, or two such cut nearly at right angles to the axis, one superposed over the other, give striking interference figures, consisting of a dark cross and isochromatic rings as explained below. If such a section be inserted between the nicols in the manner that the Bertrand lens (p. 50) is inserted at *U*, figure 54, the interference figure is distorted except when any axis of ether vibration of the mineral (p. 53) lies in the plane of the principal section of one of the nicols. When the figure is true the mineral is at the extinction position.

*Quartz sensitive plate.* Another method of determining the point of extinction depends on a distinction of difference of color. A thin quartz plate is cut parallel to the axis, having such a thickness that it shows the violet color of Newton's scale (p. 57), when put between crossed nicols in such a position that its axis stands at an angle of 45° with the nicols. This plate may be mounted and inserted at U, figure 54. In use, the field of the microscope being violet, a thin section of the mineral under examination is cautiously placed on the stage and drawn into the focus so as not to occupy the whole field. That part of the field which is occupied is differently colored from the rest. On rotation of the stage, carrying the thin section, the two parts of the field may be made to show the same violet color. When no difference exists between them the thin section is at the extinction point. This is because the axes of ether vibration of the nicols and of the thin section are in the same position, producing no interference. The color throughout is dependent solely on the quartz plate.

*Bertrand ocular.* This apparatus brings the contrast of color somewhat more effectively before the eye, and has the advantage of being applicable with high powers to small fragments of a mineral. Two pairs of right and left handed quartz are cut perpendicular to the axis, ground to the same thickness and cemented together in alternate order so that their edges meet at a common point, at right angles. This compound plate, when set in the ocular with its cemented edges exactly in agreement with the crossed nicols, (one of which must be above the ocular)* presents but one tint of color. If a thin section of a doubly refracting mineral be put on the stage in the focus of the microscope, the quadrants are differently colored, (except in the extinction position), in regular alternation, the opposite quadrants being similar. On rotating the thin section the quadrants become alike when the point of extinction is reached. The axis of ether vibration of the section then lies in the principal planes of the nicols.

*Interference figure in convergent light.* In order to distinguish a uniaxial crystal, cut at right angles to its optic axis, from an isotropic crystal, resort is had to its "interference figure," (figure 56) in convergent polarized light.

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* For this the student must use the special (third) nicol, which is not attached to the microscope.

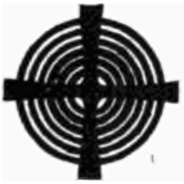

**Fig. 56. Uniaxial Figure.**

This is done by bringing the lens for producing convergent light close up under the glass plate carrying the thin section and examining the section with a high power objective. After focusing the objective the ocular is removed from the body of the microscope. On looking into the top of the tube, the nicols being crossed, a distinct black cross, sometimes with colored rings. is seen in the further end of the objective, the arms of which have the same direction as the sections of the nicols. On rotating the crystal on the stage this dark cross is not affected if the section be accurately perpendicular to the optic axis. If, however, it be somewhat oblique the figure will move about the centre of the field. If it be still further oblique, the centre of the figure may be outside of the field of the microscope and on rotation only its dark bars can be seen to move across the field. It should be noted here that *these dark bars are continually straight and parallel with themselves.*

But if the obliquity of the section be so great that the centre of the interference figure is thrown outside of the field of the microscope, the black bars begin to show a curvature, increasing with the obliquity, on entering and on leaving the field, becoming straight only when they cross the centre of the field. It should again be noted, in order to distinguish these dark curved bars from those of biaxial crystals, that the curvature shifts from one direction to the other in crossing the field, and that it swings about the ends of the horizontal or vertical diameter of the field. This fact distinguishes the uniaxial bars from the dark bars of biaxial crystals which, under such circumstances, remain always curved in the same direction in passing across the field. They both become straight when the plane of the optic axis lies in the principal section of either nicol (p. 46).*

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* Still, if the obliquity of the biaxial crystal happen to be in a direction parallel to the optic plane, the dark bar will present an appearance similar to that of the oblique uniaxial crystal.

If the section be so oblique that it is nearly or quite parallel to *c* the black cross which appears breaks up, on rotation of the stage, into hyperbolas which are symmetrically placed with respect to the optic axis. On further rotation these hyperbolas unite to form a dark cross again.

If the black cross be accompanied by colored concentric rings, they are produced by the double refraction and ultimate interference of rays from the circular convergent lens (p. 42). The appearance of colored rings depends on the strength and quality

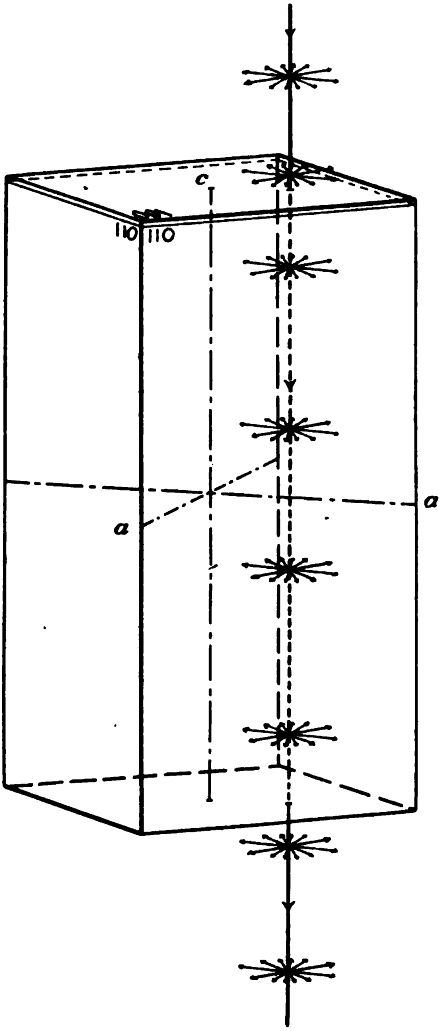

**Fig. 57.** Ray advancing parallel to the vertical axis.

of the double refraction of the mineral, and on the thickness of the plate.

Axes of Ether Vibration. The directions in which ether vibrates in anisotropic substances with the greatest and the least ease are the *greatest* and *least axes* of *ether vibration*. These axes are always perpendicular to each other.

*The greatest axis of ether vibration* is denoted by the letter X. This is equivalent to $n_p$, in French texts, and to $\mathfrak{a}$ in German. The index of refraction of light vibrating in this direction is expressed by $n_p$, or in German texts by $\alpha$.

*The least axis of ether vibration* is denoted by Z, or in French texts by $n_g$, and in German texts by $\mathfrak{c}$. The index of refraction of light vibrating in this direction is expressed by $n_g$, or in German texts by $\gamma$.

In uniaxial crystals one of these axes always coincides with the vertical crystallographic axis; the other is in all directions at right angles to this. That which coincides with the vertical crystallographic axis may be the greatest or the least axis of ether vibration, according to the mineral.

The student must not conceive of these as lines having positions, within a crystalline substance, but as directions. Light is propagated along these directions in ether vibrations respectively perpendicular to them.

The accompanying figures illustrate the directions of ether vibrations in uniaxial crystals for rays parallel, perpendicular and oblique to the vertical axis, (figures 57, 58a, 58b, 58c, 58d and 58e).

For a ray advancing parallel with the vertical axis of a uniaxial crystal as in cassiterite, figure 57, the ether vibrations may be perpendicular to its direction of propagation on all sides, and the ray is not doubly refracted, nor polarized.

For a plane wave advancing perpendicular to the vertical axis, while there is no refraction the *E* ray suffers retardation and is polarized at right angles to the *O* ray, as represented in figure 58a. This figure represents cassiterite, and the retardation of the *E* ray is accurately constructed. It is one tenth of the distance traveled when passing through the crystal in the direction shown. The ether vibrations of the *E* ray are in a plane at right angles to those of the *O* ray.

For a plane wave advancing obliquely to the vertical axis, the *E* ray has ether vibrations in the plane of the ray and the vertical axis, and the *O* ray at right angles to that plane. Figure 58b also represents cassiterite. The retardation of the *E* ray, when passing through the crystal in the direction shown is four hundredths of the distance traveled, and is accurately constructed in the figure. In this case the incident ray is polarized in the same manner as in figure 58a, but the *O* ray passes straight through without refraction, while the *E* ray is refracted and its direction altered while in the section—but the direction of wave propagation is always the same.

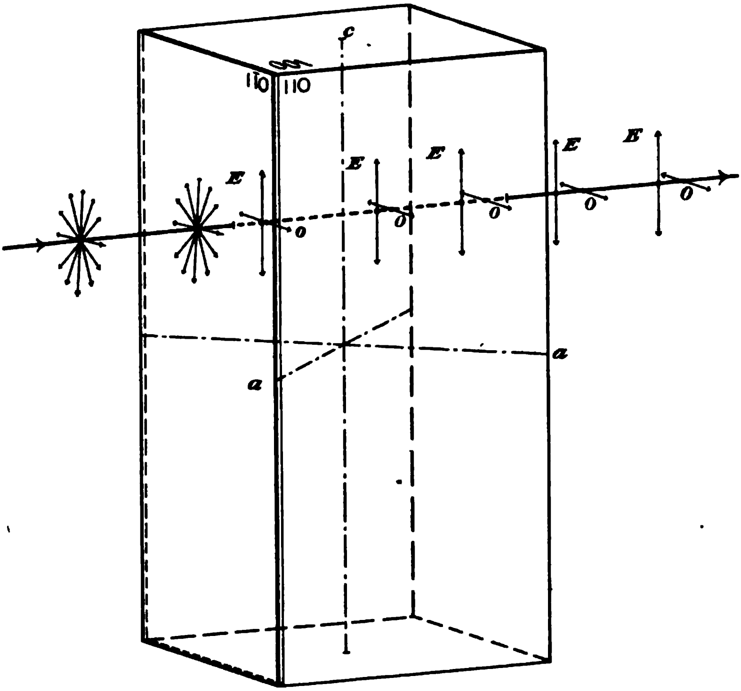

**Fig. 58a. Plane wave advancing perpendicular to the vertical axis, showing ether vibration and retardation of the *O* and *E* rays.**

In figures 57, 58a, and 58b the incident ray is normal to the crystal surface. In figures 58c, 58d, and 58e the incident ray falls obliquely upon the crystal surface. In these more general cases we have typical "double" refraction, since with oblique incidence both rays are refracted, although unequally. In figure 58c the incident ray strikes a surface normal to the vertical axis; the figure shows the retardation and the deviation of the *E* ray as compared with the *O* ray in cassiterite.

In figure 58d the incident ray impinges obliquely upon a surface parallel with the vertical axis, and here also the retardation and deviation of the *E* ray are shown. In figure 58e the most

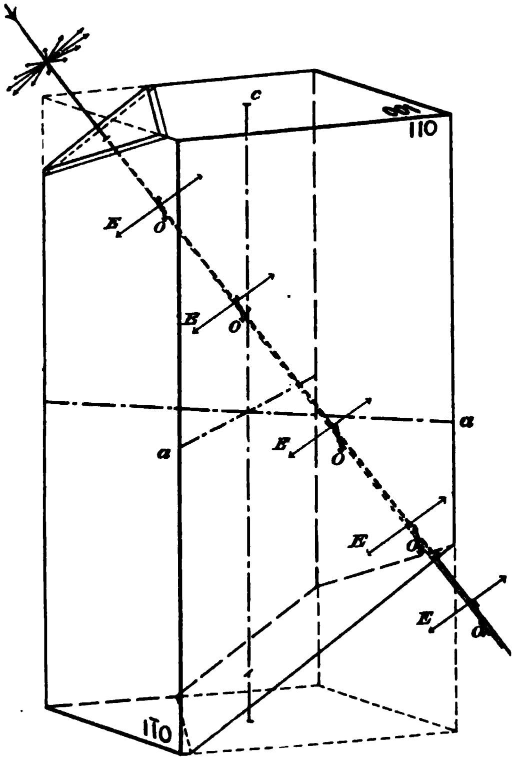

**Fig. 58b.** **Plane wave advancing obliquely to the vertical axis through a uniaxial crystal.**

general case is illustrated, since the incidence is inclined upon a crystal surface of indefinite position; the retardation and deviation of the *E* ray are illustrated as occurring in cassiterite.

Newton's Color Scale. It has been stated (p. 46) that anisotropic media, in thin section not perpendicular to an optic axis, between crossed nicols show polarization colors except at extinction positions. These colors are among the most characteristic phenomena of such minerals, and they have to be studied with great care and with special apparatus.

In order to have a standard for comparison the color scale of Newton has been adopted. This consists of a succession of interference tints (see plate at the end of the volume) shading in each direction into each other, depending on the varying thickness of a refracting medium. The same succession of tints is produced by doubly refracting mineral sections. At certain points in this scale the colors have been named, making about forty distinguishable tints in natural light (table). Certain colors recur with some regularity, and they all fade out when the section is either very thin or very thick. They are best exhibited by thin sections having a thickness from 0.01 mm to 0.06 mm.

*The lowest colors* are those of the first order embracing 18 distinguishable colors. The next 14 colors constitute the second order, and the next 9 the third. In the fourth order the colors blend by overlapping of the interference, and gradually approach white light. It will be noticed that the recurrence of the *violet*

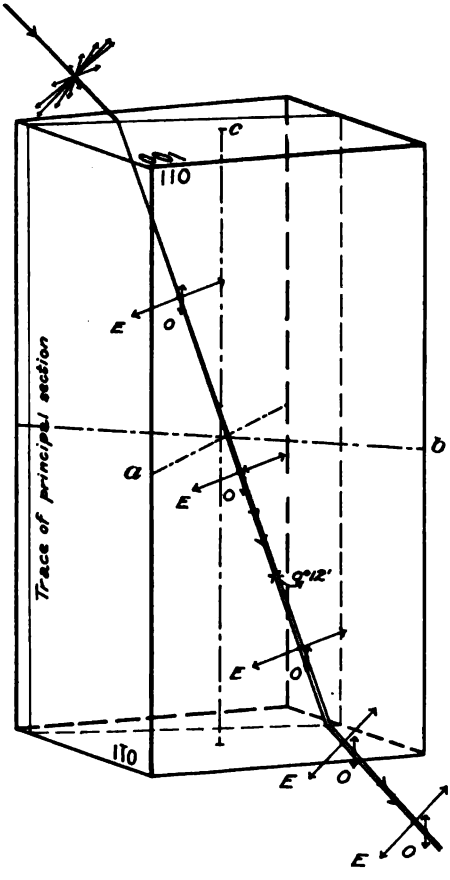

Fig. 58c.

**Double refraction, polarization and retardation for oblique incidence on a plane normal to the optic axes in a uniaxial crystal.**

*color* marks the limits of the "orders." This color is often used for reference. The first occurrence of violet is known as the "*sensitive tint*" (*teinte sensible*) No. 1. The second is *sensitive tint* (*teinte sensible*) No. 2.

In making comparisons with this scale, it is always understood, unless otherwise mentioned, that the colors of the mineral examined are the highest such a mineral is capable of producing, viz: in uniaxial minerals in sections cut parallel to the optic axis, and in biaxial minerals in sections cut parallel to the axial plane in which lie the greatest and least axes of ether vibration; also that these colors are most brilliant when the extinction positions of the mineral section are at 45° with the sections of the nicols.

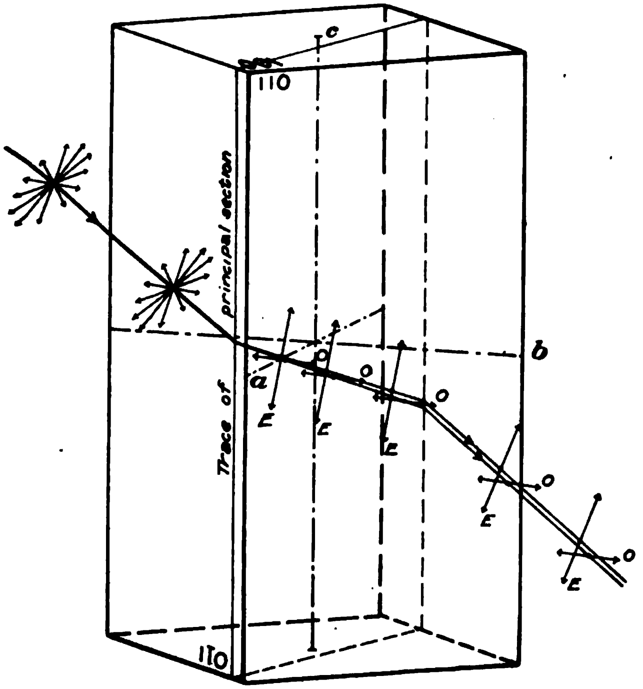

Fig. 58d.

Oblique incidence on a surface parallel to the optic axis.

From what has been said it will be evident that for ordinary light, and a known thickness of a thin section, the highest interference color will depend on the double refraction of the mineral, which is a constant element; i. e., in uniaxial crystals on the difference between $\omega$ and $\epsilon$, and in biaxial crystals on the difference between the indices of X and Z, or $n_g - n_p$, (see p. 64); and since the thickness of the thin sections ordinarily used may be considered, in practice, substantially uniform,* the polarization color becomes at once a guide to the comparative value of the indices of refraction in any mineral.

Quartz Sensitive Tint, which is often used to detect exactly the position of the greatest extinction of light, (p. 49) is conveniently employed in comparison with colors of objects examined between crossed nicols. It consists simply of a plate of quartz cut parallel to its vertical or small axis (Z) of ether vibration and of such thickness that it uniformly gives the first violet color of Newton's scale.

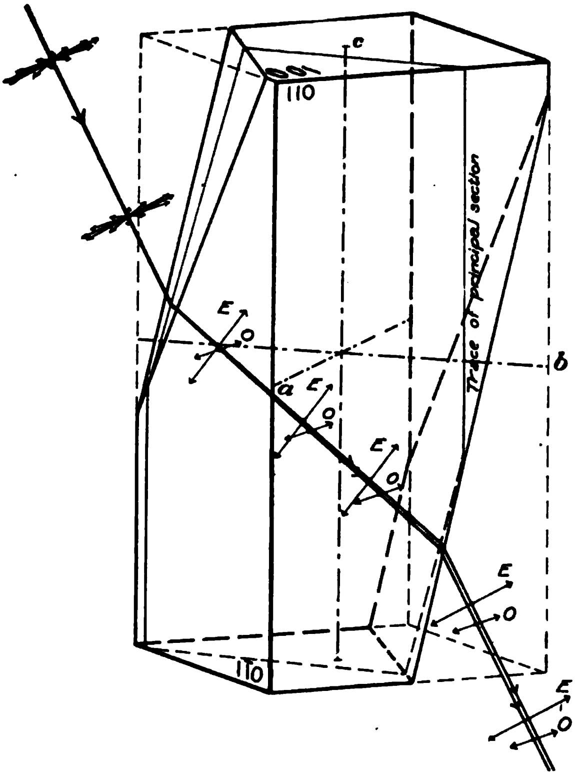

Fig. 58e.

Inclined incidence on a surface of indefinite position with respect to the optic axis.

Quartz-Wedge. This consists of a similar quartz plate, but of varying thickness. It hence gives all the colors of Newton's scale, ranging from the grayish-blue of the first order to the sensitive tint No. 2, between the second and third orders or further. When mounted for use its axis should stand at 45° with its long edge.*

---

* Thin sections must be of uniform thickness, and not over 0.03 mm, in order to be amenable to the descriptions of this work. That is the limit set by the French petrographers.

Since it is impossible to make a quartz wedge whose thin edge reaches an ideal vanishing point it is not possible to compensate interference colors below that produced by a difference of phase of about a quarter of a wave length with an ordinary quartz wedge. But Wright ** has devised a combination wedge which overcomes this difficulty. This instrument consists of a plate of gypsum of uniform thickness upon which a wedge of quartz (or gypsum) is placed in such a position that the faster ray in the gypsum is the slower ray in the quartz. The gypsum plate is made of such thickness that its effect is completely compensated by that of the wedge at the middle of the latter. At this place therefore, the wedge produces darkness between crossed nicols; if the wedge be moved in either direction the colors rise gradually from this zero effect to the third order. If this wedge be superposed over a mineral section the colors will rise as it is moved in one direction from the center and fall as it is moved the other way.

DETERMINATION OF THE ORDER OF COLOR PRODUCED BY INTERFERENCE. With the quartz wedge the rank of an interference color is determined. Suppose a thin section shows red, when its extinction direction is at 45° with the nicols. As red occurs in Newton's scale at three points, it will be difficult, in many instances, to decide to which order the color belongs. In order to determine its rank the thin section should be placed, between crossed nicols, at an angle of 45° from extinction. It must now be ascertained in which direction in the section the smaller axis of ether vibration lies. If the quartz wedge be inserted with its axes parallel to those of the section, the color of the thin section will either rise or fall in the scale of Newton; i. e., it will ascend from the first order upward, or *vice versa.* If the color of the section, on pulling the wedge into the slot, rise successively from one color to the other, such change indicates that the greater axis of the thin plate is parallel with the same of the quartz wedge, and the wedge must be withdrawn and inserted again with its axis at 90° from its former position. This is done simply by turning the wedge over before insertion. In this case the colors will fall, and the smaller axis of ether vibration of the section is parallel with the greater axis of the quartz wedge. Having thus determined the position of the smaller axis of ether vibration of the section, the quartz wedge should again be inserted gradually in such a manner that the greater axis of one is parallel to the smaller of the other. The colors then successively descend in the scale as thicker parts of the wedge come over the plate, until a point is reached, called the *compensation point,* where the acceleration of one of the rays of the plate corresponds exactly to the retardation of the same in the quartz wedge, and the plate becomes gray or dark. If the two plates could, in this position, be viewed separately between crossed nicols, they would be found to possess the same coloration and the same luminous intensity if equally transparent. Let the section now be withdrawn entirely, and as the quartz wedge is then slowly withdrawn in reverse order to that in which it was inserted, the colors can be counted as they succeed each other to the thin edge, giving the order of the original red of the section.

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* It should be noted that some quartz plates of sensitive tint, and some quartz wedges, are not made in the manner above described with an arrow indicating the axis at 45° with their longer edge; but have their axes parallel with their longer sides.

** F. E. Wright, *T. M. P. M.* Vol. XX. 1901. p. 275. *Jour. Geol.* Vol. X. 1902. p. 33.

MEASUREMENT OF DOUBLE REFRACTION: It sometimes becomes necessary to make more precise distinctions. For this purpose a special apparatus (comparator) has been devised by Michel Lévy. It is adapted for use with the microscope of Nachet, and may be adjusted to any microscope. This instrument is illustrated below by figure 59. Its purpose is, in brief, to compare the double refraction of any mineral, when placed on the stage of the microscope between crossed nicols, with that of a known mineral. For this standard quartz is chosen.

The instrument consists of a small mirror, *A*, from which a ray is sent by reflection from *B*, through the small horizontal tube which contains crossed nicol prisms (situated at *C* and *C'*) into the ocular *G* which is inserted in the microscope in the usual manner. This ray passes through the quartz wedge *F*, which ranges through the colors of the first and second orders and up to the green in the third order, and which can be made to stand at an angle of 45° with its crossed nicols, and also to move slowly by the thumb-screw *E*, bringing its various thicknesses before the small aperture, which admits the ray to the nicol *C′*. This movement is registered at the vernier *D*. At *H* the ray passes through a small lens having a long radius. In the line of its course in the ocular *G* it meets another reflector which sends it upward to the eye. It is evident that it shows the color that may be produced by the small quartz wedge. The reflector in *G* has a small aperture so situated that the colored light from a thin section placed on the stage between crossed nicols comes into contrast with that from the comparator.

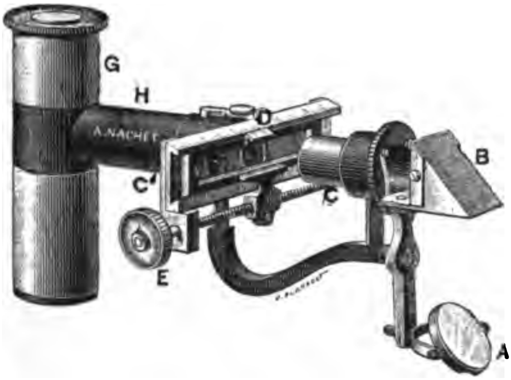

**Fig. 59. Michel Lévy's Comparator.**

In order to use this comparator, it is first necessary to ascertain the constant of the quartz wedge, *F*, that is to say, the value of one of the smallest divisions of the scale *D*, including its vernier, in the units of Newton's scale. This is done by taking the readings of the comparator scale when its quartz wedge (*F*) stands successively at the two *sensitive tints*. Suppose, for instance, these two readings are 345 and 707, the difference is 362. In the table of Newton's color scale these positions have the readings 575 and 1128; hence,

One division of the scale, or

$$d_1 = \frac{1128-575}{707-355} = 1.56 +$$

This value expresses the ratio between the units of the quartz comparator and those of the scale of Newton. This value is not noticeable in the change of color for one unit, but is applicable between the distinguishable tints.

In making use of this co-efficient, let a mineral thin section of the proper thickness which gives some one of the colors of Newton's scale be placed on the stage of the microscope. With the quartz wedge of the comparator at 45° with its nicols, let the color of the mineral be brought to agreement with that of the comparator by means of the milled screwhead *E*. Suppose the reading of the vernier (*D*) then is 749; its product by the co-efficient above gives the amount of retardation of the specimen, or 1142.974, approximately 1143 millionths of a millimetre which, by the table, is about that of epidote, pectolite, gilbertite and talc.

Measurement of the thickness of the section. But this result is dependent on the thickness of the section, represented by *e*, and has no value until that element can be measured or eliminated. The most direct method of measuring the thin section is with the fine adjustment of the microscope; which is made to focus the objective (with some high power) first on a dust particle on the upper part of the thin section, lying in the Canada balsam, and then on another on the other side. The difference in position of these focal points is read from the graduated screwhead of the fine adjustment. It is well to make several trials, taking their average. In the Nachet microscopes the complete revolution of the milled head amounts to one-fourth of a millimetre, that being the tread of the screw of the fine adjustment. The graduation on the rim divides this into hundredths, and the vernier again divides these into fifths, rendering it possible to record the thickness to within $\frac{1}{2000}$ millimetre. The approximation, however, owing to variation in the thickness of sections in different places and to difficulties in the focusing of the common objective with white light, rarely reaches closer than $\frac{1}{200}$ millimetre.

The errors are best eliminated by using ocular No. 3 with immersion objective No. 7, and a strong light sifted through a dark-red glass. One then can observe the brilliant diffraction circles which appear about the dust particles when above or below their focal points.

Suppose the section, whose retardation has been found above to be 1142.974, has a thickness of 0.03 mm. This value may be freed from the element, (*e*), the thickness of the section, by laborious methods, or by reference to the table of double refraction prepared by Michel Lévy, in which the results of numerous calculations are graphically expressed in a condensed form. The figure which we have obtained would fall near 1151, at the top

## APPLICATION OF NEWTON'S COLOR SCALE
## TO THE PRINCIPAL ROCK-FORMING MINERALS, IN PLATES 0.03 MM THICK

NOTE:—This table is essentially a condensed expression of facts contained in Plate I, which is a reproduction of Michel Lévy's Tableau des Biréfringences

| *Millionths of a Millimetre Retardation* | *Interference Colors between Crossed Nicols* | *Interference Colors between Parallel Nicols* | *Value of $n_g - n_p$ (Approximate)* | *ROCK-FORMING MINERALS Mineral Species* |
|---|---|---|---|---|
| 0 | **Black** | **White** | | |
| 30 | Iron Gray | Yellowish White | 0.001 | Leucite, Pennine, Analcite, Apophyllite, Gmelinite |
| 60 | Lavender Gray | Yellowish White | 0.002 | Vesuvianite, Tridymite |
| 90 | Lavender Gray | Yellowish White | 0.003 | Chabasite, Phillipsite, Eudialyte, Ripidolite |
| 117 | Lavender Gray | Yellowish White | 0.004 | Apatite |
| [illegible] | Bluish Gray | Brownish White | 0.004 | [illegible] |
| [illegible] | [illegible] | Grayish Blue | 0.048 | Diaspore, Limonite |
| 1480 | Rose Red | Sea Green | 0.049 | Fayalite |
| 1495 | Rose Red | Sea Green | 0.050 | Octahedrite, Talc |
| 1534 | Light Carmine Red | Green | 0.052 | Acmite |
| 1621 | Purplish Carmine | Dull Sea Green | 0.054 | Astrophyllite, Talc(?) |
| 1652 | Violet Gray (Sensitive Tint No. 3) | Greenish Yellow | 0.056 | Grünerite |
| 1811 | Light Brownish Green | Carmine | 0.060 | |
| 1845 | Greenish Gray, nearly White | Brownish Yellow | 0.062 | Zircon |
| 2040 | Reddish Gray, nearly White | | 0.068 | Vermiculite |
| 2170 | Colors very faint | | 0.072 | Hornblende (basaltic) |
| 2900 ± | | | 0.097 | Cassiterite |
| 3600 ± | | | 0.121 | Titanite |
| 4600 ± | | | 0.155 | Aragonite, Brookite |
| 5200 ± | Not Distinguishable | | 0.172 | Calcite |
| 5400 ± | | | 0.179 | Dolomite |
| 6100 ± | | | 0.202 | Magnesite |
| 7200 ± | | | 0.239 | Siderite |
| 8400 ± | (With shades of Red and Green) | | 0.280 | Hematite |
| 8600 ± | | | 0.287 | Rutile |

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of the colored plate, which is the amount of retardation for the color indigo in the third order (p. 57), and applies to any mineral giving this color having a thickness of 0.06 mm. Its double refraction is expressed at the top of the color scale in a line directly below the figures 1151, and amounts to about 0.0192. For the section selected, which is 0.03 mm in thickness, the double refraction ($n_g - n_p$) is found by tracing the oblique line which, at a point directly below, intersects the horizontal line corresponding to the thickness of 0.03 mm upward toward the right to the top of the color scale, where it coincides with the value of 0.038, which is the figure sought, i. e., $n_g - n_p$.

This method is applicable to both uniaxial and biaxial minerals, since double refraction in biaxial minerals depends upon the difference in velocity of the rays vibrating parallel to the least and greatest axes of ether vibration.

The table of double refraction above referred to is otherwise also very useful. The oblique lines cut the horizontal lines in those points which correspond to the various values of $e$X (X $=$ $n_g - n_p$) for each thickness of a plate from 0.0 mm. to 0.06 mm. This gives immediately a ready differential character by means of which at a glance some of the minerals, common in rocks, can be distinguished from each other by their polarization colors, when their other optic properties are nearly identical. Thus, in a section of zircon, thickness of 0.92 mm. the maximum color, is greenish-blue of the third order. Rutile, on the contrary, does not afford chromatic polarization at this thickness, but appears the same as in natural light. Enstatite and hypersthene have double refraction which is about half that of augite and hornblende. Zoisite and epidote, blue corundum and blue tourmaline are distinguished in the same way.

This table is useful, also as a means of determining what color a given mineral of a given thickness would present between crossed nicols when cut in thin section parallel to its optic plane.

The table adjoined, showing the succession of colors of Newton's scale, contains also a column of figures, calculated from the table of Michel Lévy, intended to show the amount of retardation for a thickness of 0.03 mm, this being the thickness of thin sections when properly made. It is evident that if there be no irregularities in the section, the amount of retardation for any thickness of the minerals named, either greater or less than 0.03

mm. can be computed from the figures in this column, since they are directly proportional to the thickness of the plate.

THE BERTRAND LENS is a device for magnifying the interference figure when it is indistinct, or when it is desired, as in the case of biaxial crystals, to measure the angle of the optic axes (p. 73), or to make a drawing of it. It is a small lens and serves, with the ocular in position, as an objective of low power to greatly increase the size and distinctness of the interference figure. It is inserted at *U,* figure 54, the lower end of the main tube of the microscope. It is focused on the interference figure by the rachet at the upper end of the tube. (See also p. 42).

THE PRINCIPAL OPTIC SECTION of a uniaxial mineral is that plane which passes through the incident ray and the optic axis; and to it the ether vibrations of the ordinary ray are perpendicular, and those of the extraordinary ray parallel.

In uniaxial crystals the optic axis and one axis of ether vibration coincide. (compare p. 46).

SECTIONS OF UNIAXIAL CRYSTALS PARALLEL TO THE VERTICAL AXIS show in convergent white light, colored curves of a form similar to that of the isochromatic curves of biaxial crystals (p. 72). In some cases only dark bars are seen which recede as hyperbolas on rotation and again unite to form a dark cross (p. 51).

*Laboratory illustrations*: The student should make numerous trials of all the methods detailed above. Thin sections of tourmaline or of olivine are useful to familiarize him with the use of the color scale of Newton. He should note the differences between the colors of these minerals and those of calcite. He should compare them also with the colors of the quartz plates.

## DETERMINATION OF THE SIGN IN UNIAXIAL MINERALS.

This consists in determining the relative values of $\omega$ and $\epsilon$, which are the symbols used to represent the indices of refraction of the ordinary and extraordinary rays respectively, in uniaxial crystals, for light traveling perpendicular to the vertical axis. $\omega$ may be greater or less than $\epsilon$, as the vertical axis $c$ may be greater or less than the horizontal axes. If the vertical axis is the direction of the greatest axis of ether vibration, the crystal is said to be *negative,* or $\omega > \epsilon$; i. e., the extraordinary ray is less refracted than the ordinary, and advances with greater velocity. Optically positive uniaxial crystals are those in which $\omega < \epsilon$.

The greater the velocity the less the refraction and the smaller the index of refraction.

The ether vibrations of the ordinary ray are perpendicular to the primary axis, and those of the extraordinary are parallel to it.

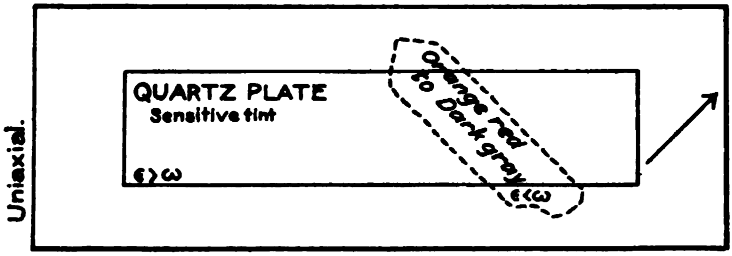
The problem consists in comparing the velocity in the two directions within the thin section, with the known velocities of another mineral. It is to be remembered that the aggregate refraction of a thin section depends also on the thickness of the plate through which the refracted light passes. Hence the elements of the problem are all in hand and it only remains to make the practical application. It may be accomplished in several ways:

1. By the *quartz of sensitive tint in parallel polarized light.* This quartz plate has been defined on page 58. As usually mounted, the plate lies between two glass strips of convenient size, with its long edge parallel with the long edges of the glass strips. The direction of its crystallographic axis, which is also the optic axis and corresponds with the direction of least velocity (i. e. with Z), is inclined 45° with the sides of the plate, as shown by the arrow engraved on the glass. By simply turning over the plate, its axis is brought into a position at right angles to its former position; i. e., the arrow is changed from pointing NW to SW or *vice versa.*

It is first necessary to determine the position of the axes of ether vibration in the mineral thin section, i. e., the positions at which, on rotation between crossed nicols, extinction takes place (p. 49), and then to rotate the stage carrying the section to a position of 45°, from these extinctions. The section then gives its brightest interference color, and the difference of phase shows its maximum effect. The quartz plate is then introduced between the nicols in such a position that the direction of the axis (Z) is 45° with their principal sections. The change of color produced by this interposition depends on whether the two axes which lie in the same direction are the same in the thin section and in the quartz plate. If they together show a color higher than the *sensitive tint* of the quartz plate, (i. e., first violet of Newton's scale), the axis of ether vibration which is in agreement with the axis Z of the quartz plate, is the same as that of the quartz plate; viz., Z, and the axis which is normal to this in each is that of the axis X. If, however, the resultant color be lower than that of the quartz plate, then the axis of ether vibration in agreement with the least axis of ether vibration of the quartz plate is the greater axis of ether vibration of the mineral. The former result is in consequence of an increase of the retardation due to the retardation of the same ray in both plates when in parallel position, and the latter to the lessening of the retardation by the superposition of a non-agreeing quartz plate.

When the color rises in sections whose double refraction color does not exceed yellow of the first order, there is apparent a tendency to change from the sensitive tint toward the yellow of the second order through green, and when it falls there is a tendency to pass toward yellow of the first order through red. Sections whose interference color is higher than yellow of the first order, should be examined by the quarter-undulation mica-plate, as below. This method is preferable, therefore, only with minerals whose maximum double refraction does not exceed two-thirds of a wave-length; e. g., the twin lamellae of feldspars, sections of quartz, chalcedony, cordierite and feldspathic spherulitic growths.

*In parallel polarized light.*



*Color falls: Negative.*

**Fig. 59a. Use of the quartz sensitive tint.**

To apply this method to the determination of the sign it is to be observed that uniaxial minerals are positive when Z coincides with the optic axis and negative when X forms the optic axis. Now the optic axis is parallel with the vertical crystallographic axis; therefore, whenever the crystal form permits the determination in the section of the position of the vertical axis the sign can be obtained by determining whether this direction is Z or X. For the determination of the sign by this method the section must be approximately parallel with the vertical axis, and the crystal outline must be distinct. But by the use of convergent light, the determination may be possible without the crystal outline. (See 6, below).

2. *By the quartz wedge in parallel polarized light.* The use of the quartz wedge (p. 58) is governed by the same prin-

ciples as the use of the quartz of sensitive tint, and is already described on page 65. It is to be inserted in the same manner and under the same conditions. Its various colors are raised or lowered in the color scale of Newton precisely as in the use of the quartz of sensitive tint, and the changes indicate the same.

3. *With the quarter-undulation mica-plate in parallel polarized light.* This is simply a cleavage leaf of muscovite of such thickness as to produce a retardation of a quarter of a wave-length, i. e., about two of the larger vertical divisions of the colored plate of Michel Lévy. It is mounted in the same way (figure 60), and an arrow shows the direction of the least axis of ether vibration (Z) at 45° with the long sides of the plate.

The principle is the same as that of the use of the quartz plates above, i. e., when the coinciding axes of the mica-plate and of the mineral are the same (Z), the double refraction is increased in proportion to the resultant thickness of the two plates and the color of the section rises through two of the larger, vertical divisions of the scale of Newton, as represented by Michel Lévy. If they are not the same the color falls the same amount. It should be noticed that with the quartz plates the point of departure is the color of the quartz, but with the mica-plate the comparison is made with the color of the section examined.

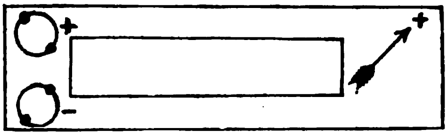


**Fig. 60. Quarter-undulation Mica Plate.**

The mica-plate is useful with sections that give a retardation of more than a third of a wave-length; that is to say, those that exceed the white of the first order of Newton's scale. Its use is hence supplementary to that of the quartz of sensitive tint.

All the foregoing processes in parallel polarized light fail in a case, fortunately very rare, where the section studied is extremely doubly refracting, and falls in the upper grays of the fourth order. In order to determine the sign of such a substance, it is necessary to resort to processes dependent on convergent light.

Still the quartz wedge can be used to good advantage in parallel light when the interference color of the section examined, is not higher than the colors given on the color plate of Michel Lévy, especially when not higher than the fourth order. In this case, when the axis (Z) of the wedge is parallel with the smaller axis of ether vibration in the section the colors will rise as the wedge is pushed forward, through higher orders, but will be almost indistinguishable; when these axes are at right angles to each other the colors will fall as the wedge moves forward, until they come to those which can easily be distinguished (colors of the third or even of the second order).

4. *With the quarter-undulation mica-plate in convergent light* (p. 67). The examination is made on the interference figure which is produced in sections perpendicular to the optic axis (figure 56). When the mica-plate (figure 60), is introduced in the usual manner, say with its axis NE and SW, the dark cross of the interference figure is destroyed, and in its place is seen a dim white cross; at the same time two dark spots appear in opposite quadrants. If the line uniting these dark spots be parallel with the direction of the arrow of the mica-plate (NE and SW), the mineral is optically negative (p. 64). If it form a cross with the direction of the arrow (i. e., the sign plus), it is optically positive. The colored rings of the interference figure, if present, are disjointed at four places, and divided into four quadrants, two of which are further removed from the centre than the other two, giving an appearance of elongation in a direction parallel to the line uniting the dark spots, while the other two quadrants are brought nearer the centre, as shown in figure 61.

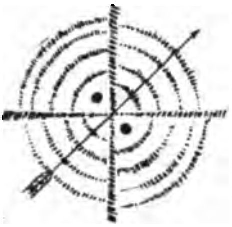


Fig. 61.

Disturbance of the Interference Figure of a Uniaxial Crystal by the Quarter-undulation Mica Plate.

These changes in the rings are caused by the change in the relative phase of the vibrations as they pass the mica-plate. The original symmetry of the interference figure is due to the symmetry of structure of the crystal about the vertical axis, which requires the interference of vibrations of like phase to fall at points equally distant round about the axis, producing the colored rings. The two axes of ether vibration which are in the mica-plate act upon their corresponding quadrants, either increasing the refraction or diminishing it, and throwing the colors in directions at right angles.

In those quadrants where the colors are moved further from the centre of the figure, the black spots appear. In these quadrants the effect of the mica-plate is to counteract (instead of increase) the effect of the mineral plate upon the light. Therefore, at the points in these quadrants where the effect of the mineral plate would be to retard one of the rays of light one quarter of a wave-length behind the other, producing a grayish-white color, the mica-plate which retards the other ray a quarter of a wave-length, counteracts this effect and produces dark spots.

5. *With the quartz of sensitive tint in convergent light.* When the interference figure is much expanded as from a thin section of a mineral of low birefringence the dark spots may be wholly outside the field. In this case a quartz plate may be inserted; two opposite quadrants will then be colored yellow and the other two blue. The yellow quadrants may be used in the same manner as the dark spots.

6. *With the sensitive tint, mica plate, or quartz wedge in convergent light.* When the section is parallel with the optic axis the interference figure is not a simple black cross, but is very similar to a biaxial interference figure in a section normal to an obtuse bisectrix. (See page 71). In such an interference figure the hyperbolas always leave the field in those quadrants in which the optic axis lies. Since these hyperbolas are always somewhat vague and move quickly across the field careful observation is necessary. When the field of the interference figure shows colors another fact may be of assistance. The interference colors for points in the quadrants containing the optic axis are lower than for corresponding points in the other quadrants. When the position of the optic axis is once determined the sign can be obtained by any one of the methods described above for parallel polarized light.

*Uniaxial Minerals* are positive when the index of refraction of ordinary ray ($O$) is less than that of the extraordinary ray ($E$); and they are negative when it is greater. For light perpendicular to the optic axis the undulations of the ordinary ray ($O$) are transverse to that axis, and those of the extraordinary ray ($E$) are parallel to it.

# BIAXIAL MINERALS.

## THE ORTHORHOMBIC SYSTEM AND POLARIZED LIGHT.

Biaxial minerals derive their name from the fact that they have two optic axes (p. 45). Light passing through the crystal in the direction of either one of these axes produces ether vibrations with equal ease in any direction perpendicular to its line of propagation. Such light, therefore, suffers no double refraction. Sections cut perpendicular to these directions remain dark between crossed nicols during a complete revolution.

The optic axes of biaxial minerals never coincide in position with any of the crystallographic axes; but in orthorhombic crystals they always lie in a plane containing two of these axes.

Orthorhombic minerals have three axes of ether vibrations (p. 53), parallel to the crystallographic axes, but the position of the optic axes varies with the mineral.

The greatest and least axes of ether vibration have already been defined (p. 53).

In biaxial minerals there is also a *mean axis of ether vibration* This is denoted by Y, or in French texts by $n_m$, and in German by 𝔟. The index of refraction of light propagated in this direction is expressed by $n_m$, or in German by $\beta$. This axis is known also as the *optic normal.*

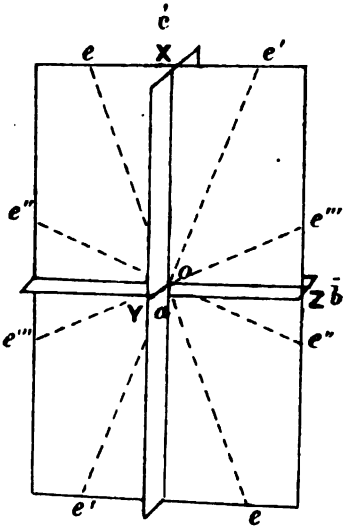


Fig. 62.

Symmetry Planes of an Orthorhombic Crystal in its conventional Position.

The direction of X may be the same as that of *c* or *a* or *b*, the directions of Y and Z varying accordingly; depending on the habit of the mineral considered; the only invariable relation being that of standing at right angles to each other, parallel to the crystallographic axes.

Let figure 62 represent the three planes of crystallographic symmetry of an orthorhombic crystal (p. 32), in its conventional position, (p. 19, fig. 7) with $c > b$. These planes contain the crystallographic axes *a, b, c*. In the figure the characters X, Y, Z indicate the directions of the greatest, mean and least axes of ether vibration respectively. These axes of ether vibration are perpendicular to the direction of propagation. Light which travels parallel to X is said to vibrate in the plane which contains Y and Z. That propagated parallel to Z vibrates in the directions X and Y, etc.

When light falls obliquely upon a surface of a crystal section in a direction oblique to X or to Z it is divided into two parts by double refraction, one part advancing in a different direction from the other part, the two vibrating at right angles to each other as in uniaxial crystals (p. 54).

OPTIC AXIAL PLANE. That plane which contains the greatest and least axes of ether vibration (X and Z) also contains the two optic axes and hence is called the *optic axial plane*, or the *optic plane*. This plane, as represented in figure 62, also obviously contains the crystallographic axes *b* and *c*.

BISECTRICES. The optic axes cross each other at the point of intersection of the optic plane with the other planes of symmetry; i. e., at *O* in figure 62, making equal angles on opposite sides of the axes X and Z. Hence X and Z are called *bisectrices*. The optic axes may be in the positions of the lines $ee$, $e'e'$, in which the angle $e\ O\ e'$ has any size less than 90° or may have the position $e''\ e''$, $e'''\ e'''$ in which the angle $e''\ O\ e'''$ is any angle less than 90°.

When X bisects the acute angle of the optic axes it is the *acute bisectrix*. When Z bisects it, Z is the *acute bisectrix*. When one or the other bisects the obtuse angle, it is called the *obtuse bisectrix*.

A BIAXIAL CRYSTAL IS OPTICALLY POSITIVE when Z is the acute bisectrix, and *negative* when X is the acute bisectrix.

Thin sections of biaxial minerals perpendicular either to an acute bisectrix or an optic axis, viewed in parallel polarized light, show lower interference colors than others of the same mineral, even to darkness, and those perpendicular to the latter do not greatly change on rotation between crossed nicols. This circumstance frequently renders it possible to distinguish them when cut in the same rock section with many others of the same mineral at differing angles, without resort to convergent light.

RELATIVE INTERFERENCE COLORS OF DEFINITE SECTIONS. The interference colors in sections of biaxial minerals which are normal to the optical elements grade downward in the following order:—

1. Optic normal
2. Obtuse bisectrix
3. Acute bisectrix
4. Optic axis

These sections exhibit, for any given mineral the greatest possible range of interference colors.

THE OPTIC AXIS IN CONVERGENT LIGHT. The interference figure of a single optic axis of a biaxial mineral, formed by convergent polarized light, is different from that of the optic axis of uniaxial minerals (p. 51). It consists, when complete, of concentric colored curves crossed by a single dark bar. In many cases, however, only the dark bar is observable. This bar when straight shows the direction of the optic plane with which it is parallel. On rotation it is slightly bent, forming the apex of a hyperbola whose convexity is turned toward the acute bisectrix. On further rotation it becomes straight again when the plane of the optic axes is parallel with the principal section of either nicol. (See figure 63).

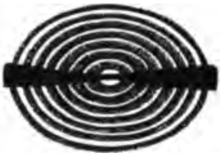


Fig. 63.
Optic Axis Interference Figure.

THE BISECTRIX IN CONVERGENT LIGHT, INTERFERENCE FIGURE. When the section is perpendicular to a bisectrix, and the optic angle is not too great, both optic axes appear in the interference figure, the bisectrix being in the centre of the field between them. The appearance then is shown by figure 64. Here a dark cross appears in the centre of the field. Its arms vary in size. That line which passes through the optic axes is less broad than that which passes between them, and its extremities widen out in the margin of the field. The bisectrix is at the point where these bars cross. *The trace of the optic plane* is the line which passes through the loci of the optic axes and the bisectrix.

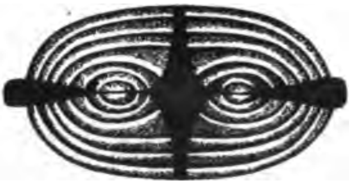


Fig. 64.
Bisectrix Interference Figure.

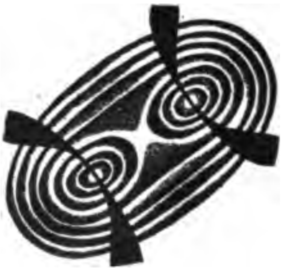


Fig. 65.
Bisectrix Interference Figure at 45°.

On rotation of the thin section in convergent light this interference figure rotates and undergoes important transformations.* The dark bars separate into two hyperbolas whose summits recede from each other toward the margin of the field, and beyond it if the optic axes are not in view. They bend through the colored curves surrounding the optic axes, and become a straight bar again when the plane of the optic axes is in agreement with either nicol. The hyperbolic summits are at their most distant positions after a rotation of 45°, as in figure 65. At the same time the colors in the lemniscates revolve, without change of shape, about the bisectrix.

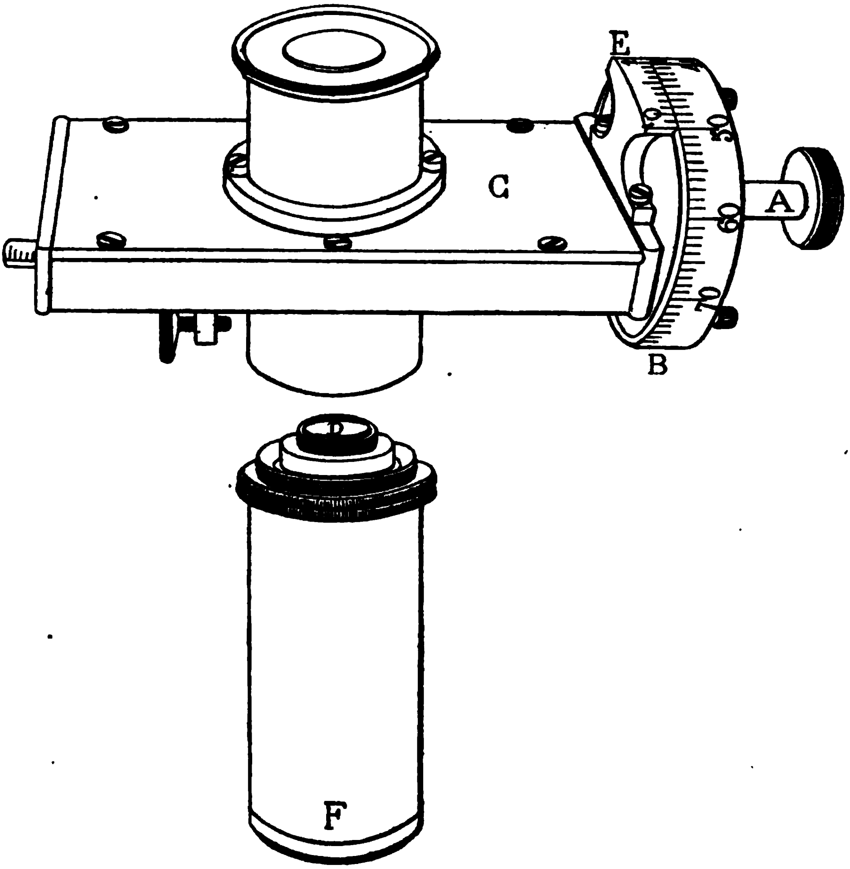


Fig. 66. Lacroix's Axial Goniometer.

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* The readiest way to observe the interference figure of biaxial minerals, is to take a thin muscovite plate, which, without further preparation, will show, between crossed nicols, in convergent light, a perfect figure, with both optic axes in the field.

MEASUREMENT OF THE OPTIC ANGLE. The size of the optic angle is an important optical character for the determination of biaxial minerals. When it is very large it cannot be measured directly by the microscope, but when it is so small that both of the axes appear within the field of the microscope in convergent light, it can be measured readily. If the object be immersed in a strongly refracting liquid, by a drop placed on the converging lens and another below the objective, both optic axes may sometimes be brought into view. For this purpose iodide of methylene is useful.

The conventional symbol for the optic angle is $2V$. When it is measured in air it has an apparent angle which is denoted by $2E$. It is represented by $2H$ when measured in oil, and by $2I$ measured in methylene iodide (Brauns' solution p. 38).

Figure 66 represents an apparatus devised by Lacroix for measuring the optic angle in air. It can be used on any microscope of Nachet, and can be adjusted to other microscopes. It is inserted in the upper end of the body of the microscope in the place of the ocular. It contains a Bertrand lens at *D* (p. 64) for magnifying the interference figure, but if the microscope have one already fitted to the lower end of the upper tube, it is better to remove the lower part of this instrument, and with it the Bertrand lens, in order to increase the delicacy of the measurement by enlarging the figure. When thus separated the lower lens *F*, of the detached eye-piece, should be screwed into the lower end of the remaining eye-piece of the goniometer. Thus adjusted it is to be used in conjunction with the Bertrand lens placed at *U*, figure 55.

When the interference figure is perfect, and the axial goniometer in position, the revolution of the graduated wheel *B*, which is independent of that of *A*, will serve to bring one of the movable

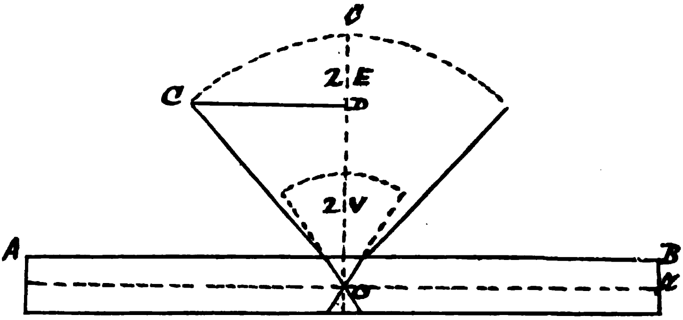

Fig. 67.
Measurement of the Optic Angle.

threads into the central point of one of the optic axes. Then by the proper rotation of *A*, which also carries the graduated rim *B*, this thread can be made to move slowly across the field and to occupy a similar position over the other optic axis. The number of revolutions, and parts of revolutions, can be read by comparison with the zero point of the vernier scale at *E*.

### *Example for the Measurement of the Optic Angle.*

In figure 67 let *O* be the point of crossing of the optic axes in the thin section of a biaxial mineral *AB*. Let $2V$ represent the acute axial angle, and $2E$ the same angle in air. The angle *COD* is one-half of $2E$, or *E*. The distance between *C* and *D* is the $\sin E$.

It is evident that the value wanted is the distance $2 \sin E$. Suppose that on trial with a thin section of muscovite it is found that the distance $2 \sin E$ is divided, by the revolution of the graduated rim *B*, (figure 66), into 1430 parts. As these parts have no known value it is necessary to compare them with a standard. Such a standard is found in a mineral whose optic angle has been previously determined by other means. For instance, if the optic angle $2E$ in another specimen of muscovite is known to be 71°, then $E = 35° \, 30'$.

Let the unknown distance between the optic axes in this muscovite be represented by $2d$, and let the unknown ratio between the units in the number 1430 and those in $2d$ be represented by *M*

Then

$$\sin E = \frac{d}{M} : M = \frac{d}{\sin E}$$

On measuring $2d$ in this muscovite it may be found to be 1525.

$$\text{Hence, } M = \frac{762.5}{\sin \, 35° \, 30'}.$$

$\log M = \log 762.5 - \log \sin 35° \, 30'$; $\log M = 3.12085$.

Therefore, in the original specimen

$$\log \sin E = \log 715 - 3.12085 = \bar{1}.73346$$
$$E = 32° \, 46' \, 31''$$
$$2E = 65° \, 33' \, 2''$$

The optic angle in muscovite may vary 30°.

In making such measurements it is necessary to use always the same objective, and to employ the same constant (*M*) ascertained for the microscope in use, which may be kept in its logarithmic form. As the apparent size of the interference figure depends on the position of the Bertrand lens, it is necessary to have the value of $M$ for several positions of that lens. Hence, it is convenient to make a small scale on the body of the tube (as at S. figure 54) by means of which the lens may be fixed in the same positions as when $M$ was established as the standard of comparison. $M$ thus will have a value for each position. This method is applicable to the optic angle in the other crystallographic systems.

When $2E$ is known the value of $2V$ can be calculated from the mean index of refraction by means of the relation $\sin E = n_m \sin V$*.

*Laboratory illustrations*: The student should get a correct idea of the optic plane and of the elements that determine its position; viz: the optic axes and the bisectrices. He should study thin sections of muscovite, and of other minerals cut perpendicular to a bisectrix, and should measure, by the use of the Lacroix axial goniometer, the optic angle in air, of one or more minerals; and then measure the same in oil.

## DETERMINATION OF THE OPTICAL SIGN IN BIAXIAL MINERALS.

A biaxial mineral is *positive* or *negative* according to whether the acute bisectrix is Z or X. Thus, in figure 62, if the optic angle *e o e′* be acute and contain the bisectrix X, the crystal is negative. If the acute optic angle *e″ o e‴* be so situated as to contain the bisectrix Z the crystal is positive (p. 71). Therefore the determination of the optical sign of a biaxial mineral requires not only the distinction of the acute from the obtuse bisectrix, but also the distinction of X from Z (as of *O* from *E* in uniaxial crystals).

*Distinction between the acute and obtuse bisectrices.* The distinction between the acute and the obtuse bisectrices is sometimes very simple, and at other times more difficult. Whenever the optic angle is so small that both optic axes, or even one optic axis and the bisectrix, remain in the field during a complete revolution the section is perpendicular to the acute bisectrix. But when the optic angle is larger it is generally necessary to find sections perpendicular respectively to X and to Z (and therefore to the two bisectrices), and make comparisons between them. As stated on page 71 the section perpendicular to the acute bisectrix will show a lower interference color than that perpendicular to the obtuse bisectrix, provided the sections are of equal thickness. Furthermore, the angle of rotation between the position of the black cross and the position where the summits of the hyperbolas are tangent to the edge of the field can be measured, and this angle for a given mineral is larger in a section perpendicular to the acute bisectrix than in one normal to the obtuse bisectrix. If the angle is more than 30° or 35° the section is normal to the acute bisectrix; if it is less than 15° or 20°, it is perpendicular to the obtuse bisectrix (or to the optic normal). Finally, if an immersion objective of large angle is available the optic angle can be measured by the method described on page 75; the acute angle is of course always less than 90°.

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* For a full description of all microscopic methods of measurement of the optic axial angle, see F. E. Wright. *Am. Jour. Sc.* Oct. 1907.

*Distinction between the axes* X *and* Z. It is to be remembered that $n_g > n_m > n_p$ to which the axes Z, Y, X, correspond respectively. The problem consists in comparing the velocity in the direction of the axis to be determined with that in the direction of a known velocity in another mineral. It is also to be remembered that the interference color depends not alone on the mineral studied but also on the thickness of the section (p. 55). When it is further remembered that the relative retardation is indicated by the relative positions of the colors produced in the scale of Newton, the apparatus used with uniaxial minerals (p. 65) can be applied to the solution of the problem. It is accomplished in several ways:

1. WITH THE QUARTZ OF SENSITIVE TINT IN PARALLEL POLARIZED LIGHT (p. 65). The process is similar to that with uniaxial minerals. It is necessary that the section examined be parallel to the axial plane; i. e., perpendicular to the optic normal (Y). The axes of ether vibration in the quartz plate are to be considered Z, in the direction of the arrow, and X perpendicular to it. When, on superposition of the quartz plate so that its axis Z coincides with an axis of the mineral in the thin section, both being at 45° with the nicols, the resultant color is higher than the *sensitive tint* of the quartz, the axes in agreement are the same; i. e., they are both Z. When the color falls below the sensitive tint the mineral contains X in agreement with Z in the quartz plate. This determines the positions of the two axes and if Z lie in the acute optic angle the mineral is positive.

To determine in which quadrants the acute bisectrix lies for a given position of the stage recourse is had to the interference figure in convergent light. This interference figure resembles that given by a section normal to an obtuse bisectrix, but is less distinct, and hyperbolas may be visible in all four quadrants if the optic angle is large. But in all cases (except the limiting case $2V = 90°$) the hyperbolas leave the field* more slowly in those quadrants in which the acute bisectrix lies than in those containing the obtuse bisectrix. If only two hyperbolas are observed they are in the quadrants containing the acute bisectrix. Furthermore, the interference colors for points in the quadrants containing the acute bisectrix are lower than those for corresponding points in the other quadrants.

The quarter-undulation mica-plate can be used in the same manner as with uniaxial minerals to determine the directions of the axes X and Z, the section being perpendicular to the optic normal.

2. In convergent light with the interference figure. If the thin section be perpendicular to one of the bisectrices, the other bisectrix is in the thin section itself along with the optic normal Y. It is to be determined whether Z or X is thus associated with Y in the section. The process is similar to the foregoing; the section is brought into such position that the optic plane (p. 72) stands 45° from the principal sections of the nicols, and the quartz plate is interposed between the nicols with its axis Z parallel with the optic plane of the mineral. If the color rise above that of the quartz plate, Z is in the section with Y, and X is perpendicular and between the optic axes. If the color fall X is in the section with Y, and Z is perpendicular and between the optic axes. In both of these cases, if the axis X is in the acute optic angle, the crystal is negative; and if Z is in the acute optic angle, it is positive. (See fig. 68.) The same colors and changes are sometimes more perceptible when viewed through the ocular.

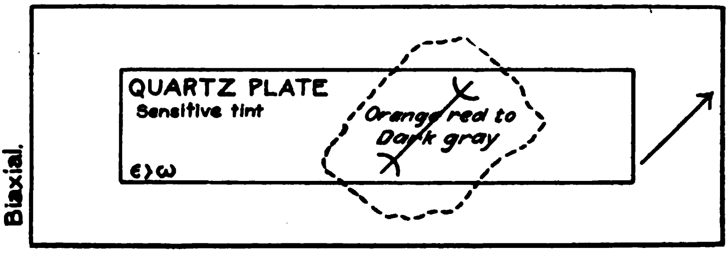

Fig. 68.
Use of the Quartz Plate in determining the Optical Sign.

3. By the quartz wedge in convergent light. The thin section must be perpendicular to the acute bisectrix, showing an interference figure. This figure is brought into the diagonal posi-

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* F. E. Wright. *Am. Jour. Sc.* Vol. XX. 1905. p. 285.

tion with respect to the nicols, and the quartz wedge is interposed, with its thin edge in advance, in such a way that the direction of the arrow agrees with that of a line passing through the optic axes of the interference figure. If the crystal be positive, as the thicker parts of the wedge are successively interposed the colors of the interference figure evolve from the optic axial spots, widen out and move toward the centre where they spread into the outer colored margins that surround the whole figure. If the crystal be negative, the movement of the colors is from the centre of the figure toward the axial spots.

4. WITH THE QUARTER-UNDULATION MICA-PLATE IN CONVERGENT LIGHT. (p. 67). This plate is perpendicular to the negative bisectrix X. It contains therefore, Z and Y; and the direction of Z is necessarily coincident with the trace of the plane of the optic axes which always contains the greatest and least indices. The arrow indicates the direction of Z, at 45° from the sides of the plate (figure 60).

When a biaxial thin section perpendicular to a bisectrix is examined with the mica-plate inserted in the usual way, whatever the position of the thin section, there is, with a negative mineral (p. 76) an apparent lengthening of the interference figure in the direction of the arrow on the mica-plate. It is best observed when the optic plane is parallel with one nicol. In this case the dark spots will appear in the quadrants through which the arrow passes, the line connecting them forming an angle less than 45° with the arrow. The reverse takes place with a positive mineral, viz., there is a shortening in the direction of the arrow, and the line connecting the dark spots forms an angle greater than 45° with the arrow. Thus, the line connecting the dark spots forms an approximate minus or plus sign with the arrow, as in uniaxial minerals. Another method has been given lately by Iddings; i. e., with the quarter-undulation mica-plate in sections perpendicular to an optic axis. The section is to be placed with its optic axial plane at 45° with the nicols; the hyperbola will then be convex toward the acute bisectrix. If the mica-plate be inserted with its axis parallel with the optic plane of the mineral, the hyperbola will move toward the obtuse bisectrix when the mineral is negative, and toward the acute bisectrix when the mineral is positive.

This method is well adapted for application to biaxial minerals of weak birefringence, for example, the feldspars. With minerals of stronger birefringence it may be seen that the apparent motion of the hyperbola upon the insertion of the mica plate is due to its disappearance and the formation of a black dot on the side toward which it seems to move. Therefore, for such cases the rule can be stated better as follows: the mineral is positive when the black dot appears on the convex side of the hyperbola upon insertion of the mica plate with its axis parallel with the optic plane of the mineral. Wright* has shown that if the sensitive tint plate be inserted in this case with its axis parallel with the optic plane of the mineral, the latter is positive if a blue spot appears on the concave side of the hyperbola, and negative if the blue spot appears on the convex side.

## EN RESUME OF THE OPTICAL SIGN.

The principles of the "optical sign" in uniaxial and biaxial minerals may be graphically represented as below: figures 69, 70, 71, and 72.

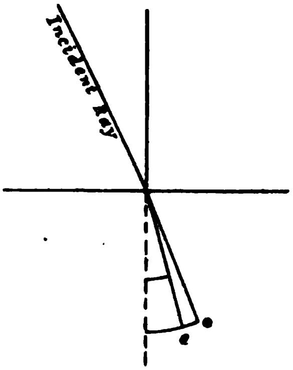

Fig. 69.
Positive Uniaxial Mineral.

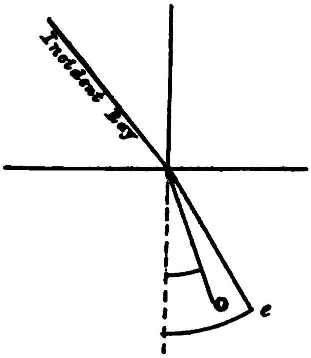

Fig. 70.
Negative Uniaxial Mineral.

*For uniaxial minerals.* When the extraordinary ray is *attracted* toward the normal after passing the plane of incidence, more than the ordinary ray, the mineral is *attractive* or *positive*, or +; $\epsilon > \omega$, as in zircon or quartz.

In this case Z coincides with the optic axis: light vibrating in this direction is necessarily the *E* ray, for which, in this case, the index of refraction is the greater one, $n_g$; the extraordinary ray travels more slowly than the ordinary ray.

When the extraordinary ray is *less attracted* toward the normal than the ordinary ray, or is repulsed, as it were, the mineral is *negative*, or —; $\epsilon < \omega$, as in calcite.

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* F. E. Wright. *Am. Jour. Sc.* Vol. XX. 1905. p. 285.

In this case X coincides with the optic axis: for the *E* ray, vibrating in this direction, the index refraction is the least $n_p$; the extraordinary ray moves more rapidly than the ordinary.

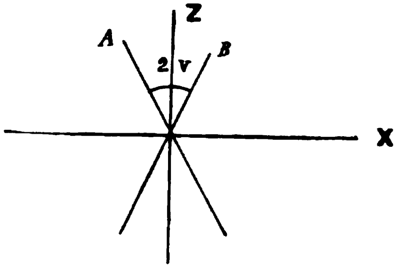

Fig. 71.
**Positive Biaxial Mineral.**

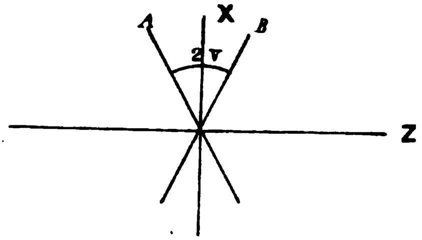

Fig. 72.
**Negative Biaxial Mineral.**

*For biaxial minerals.* When Z is the acute bisectrix it is called *positive,* and the mineral is also positive, or +, as augite.

When X is the acute bisectrix it is called *negative,* and the mineral is also negative, as muscovite.

## DISPERSION OF THE AXES IN THE ORTHORHOMBIC SYSTEM.

It has been stated that in convergent light the colors of the interference figures are caused by the difference of phase of different rays brought together by the analyzer so as to interfere (p. 46). The manner of distribution of these colors is characteristically different for the different crystallographic systems of biaxial minerals. The rays that emerge after the interference are distributed about the optic axes, which are represented by the two central points in the systems of rings in the interference figure. The phenomena of the relative positions of the red and violet rays are caused by the *dispersion of the optic axes.* Sometimes the red rays have the greater optic angle and sometimes the violet rays. These relations are expressed respectively by $\rho > v$ and $\rho < v$.

RHOMBIC DISPERSION. In the orthorhombic system these colors are symmetrically placed with respect to the bisectrix, and on rotation of the section they symmetrically follow the summits of the hyperbolas. They are best examined when the section is either in the normal, or in the diagonal position (45°).

Neglecting all other colors the attention is directed to the red and the violet rings which surround the loci of the optic axes when the interference figure is in the normal position. Of these the innermost ring is noted, whether it be red or violet. If the ring be not entirely of one color, either red or violet, it is to be noted which color occupies that portion of it which is nearest the point of emergence of the bisectrix. If the innermost ring, or that portion of it nearest the bisectrix be red, then $\rho < v$. If it be violet, then $\rho > v$.

When, in the normal position, the dark cross obscures the colors, the examination will be made in the oblique position. In that position it is to be noted which color lies nearest the dark hyperbola on the concave side. If it be red then $\rho < v$, and *vice versa*. It is sometimes so faint as to be hardly observable.

Use of red and blue light. The dispersion of the optic axes may sometimes be examined more expeditiously by the use of colored glasses. On a slide which accompanies the Nachet microscope are mounted small, square, colored glasses, red and violet. The slide is inserted in the slot (U. figure 54), in order to produce a red or a violet field. The effect is to produce, with the red glass, dark rings where the blue occurs in the interference figure, and where the red occurs with the violet glass, these colors being mutually complementary. The examination consists in making a comparison of these dark rings, bearing in mind that the dark rings produced by the red glass correspond to the position of the blue rings of the interference figure, and *vice versa*. By quickly shifting the slide so as to change back and forth from red to violet, the shapes and positions of the concentric dark rings surrounding the loci of the axes, undergo sudden changes, and can easily be contrasted (figure 73). When $\rho > v$ the outermost black ring seen when the field is red is elongated and further removed from its fellow in the other end of the figure than when the field is blue. The reverse takes place when $\rho < v$.

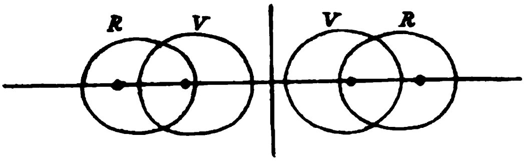

Fig. 73. Rhombic Dispersion.

Barite, cordierite, olivine, are examples of the orthorhombic minerals having $\rho < v$. Aragonite, staurolite, cerussite have $\rho > v$.

## OBSERVATION OF PARTIAL INTERFERENCE FIGURES.

The interference figure produced in convergent light is one of the most useful of the optical phenomena of minerals. In rock sections containing numerous grains of the same mineral, either an entire or partial interference figure may usually be found. When once found it serves various purposes, as may be seen by the descriptions already given. For the purpose of further elucidation, the following figures illustrate the appearances when only a portion of the figure is visible. With a little practice the presence of an acute bisectrix or an optic axis within the field of the microscope can easily be detected. By a careful study of the dark bars in rotation, the direction of the bisectrix from the centre of the field and its approximate nearness may also be determined.

For this examination the magnifying lens of Bertrand (p. 64) should be employed, with a No. 1 eye-piece and a powerful objective. If desired, the figure with its colors can be thrown by the camera lucida upon a surface lying near the microscope, and exactly drawn..

Uniaxial interference figures. Figure 56 shows the interference figure of a uniaxial mineral perpendicular to the axis. In figure 74, are seen various positions of the same figure when the section is not precisely perpendicular to the axis.

When the optic axis is outside the field of the microscope straight dark bars are seen on rotation to cross the field one after the other, as in figure 75. The locus of the optic axis is always at the intersection of these bars.

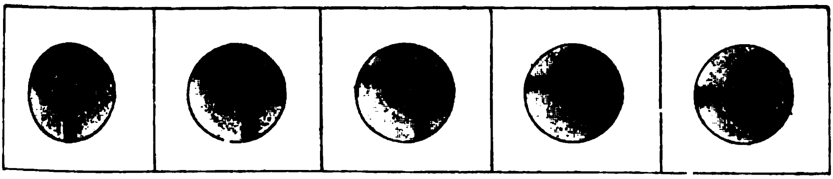

**Fig. 74. Positions of the Uniaxial Interference Figure.**

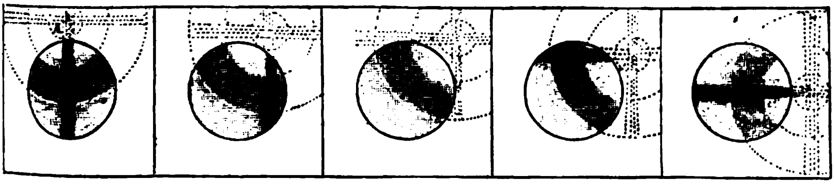

**Fig. 75. Uniaxial Dark Bars.**

This property leads to the determination, in all cases, of the sign of the uniaxial mineral (p. 80). It has been stated that when introduced at an angle of 45° the mica plate breaks up the dark cross (p. 62) and gives rise to two dark spots. If the substance is positive the line of the arrow on the plate and that connecting the dark points form the sign *plus* (+). If it is negative these lines do not thus cross, but lie parallel. In case the dark spots are at first invisible, it is necessary to determine by a partial rotation the direction of inclination of the optic axis and thus its position with respect to the field. If then the principal section of the mineral (p. 64) be made to stand at 45° with the nicols, on inserting the mica first parallel and then perpendicular to this section, generally one dark spot can be observed in that quadrant of the field nearest the optic axis. The other dark spot will be in the principal section beyond the locus of the optic axis, and the line uniting them forms + or — as before.

In case the obliquity is so great that the spots cannot be distinguished it is possible still to determine which of the directions of extinction corresponds to the projection of the optic axis by means of the dark bar crossing the centre of the field, and then to determine whether it is Z or Y by the superposition of the quartz plate (p. 58), which is best done in parallel polarized light.

When the plate is substantially parallel to the single optic axis, phenomena are produced which are somewhat analogous to those given by plates cut perpendicular to the optic normal in biaxial crystals; two equilateral dark often confused hyperbolas are seen which on rotation of the stage mutually advance toward each other and retreat forming a dark cross or a darkening over the centre of the field four times in each complete revolution.

Biaxial interference figures. Figure 76 represents the position and appearance of the dark bar when a single optic axis is visible in the field of the microscope. In this case it is easy to determine the position of the plane of the optic axes. The hyperbolas revolve about the trace of this plane in a direction opposite to the rotation of the stage. On bringing the visible hyperbola to have its greatest curvature, the trace of the optic plane will be a line at 45° with the nicols and perpendicular to the hyperbola at its summit. The acute bisectrix is situated on the side of the convexity of the hyperbola. This convexity diminishes as the optic angle increases, the hyperbola becoming a straight line in all positions of rotation, when the optic angle is 90°.

When the optic axis is outside the field of the microscope, and the inclination is in the optic plane, the various aspects of the dark bar are represented in figure 77. This dark bar is distinguishable from that of uniaxial crystals (figure 75) by the curvature which it presents (p. 72). When it becomes straight and passes through the centre of the field, it marks the position of the plane of the optic axes. If the section be not perpendicular to any principal plane of elasticity the black bars are always curved.

If one of the optic axes be near the field of the microscope, and at the same time one of the bisectrices appear within it, then the other optic axis is also near the margin of the field, and the rotation of the stage will cause the succession of changes represented in figure 78. The presence of the bisectrix is indicated by the production of the black cross which breaks up into hyperbolas by the rotation of the stage. The quadrants into which the hyperbolas disappear (NE—SW, or NW—SE) can be easily distinguished. On turning the stage slowly in the direction of the hands of the watch, if they disappear NW—SE the plane of the optic axes was previously E—W. If they disappear in the direction NE—SW the plane was N—S.

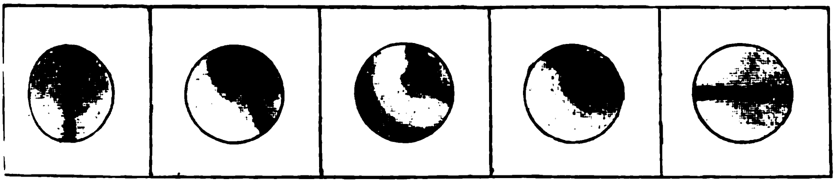

Fig. 76. Dark Bar with a Single Optic Axis in the Field.

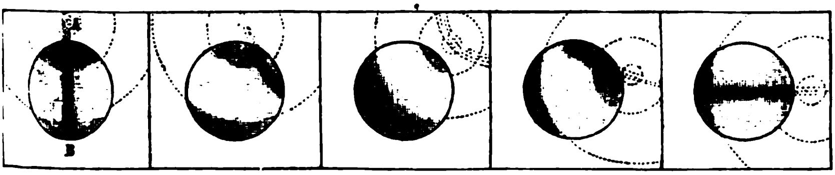

Fig. 77. Dark Bar with a Single Optic Axis Outside the Field.

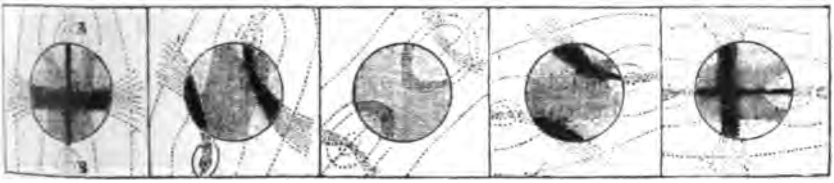

Fig. 78. Changes of the Interference Figure with a Bisectrix in the Field.

The most useful position of the axial plane may always be established on the disappearance of the hyperbolas, say NW—SE, by laying off an angle in the same quadrants, of 45° from extinction and turning the section to that position. The hyperbolas are then at their most distant points, and the bisectrix is favorably situated for examination with the quartz plate.

When neither a bisectrix nor an optic axis pierces the field of the microscope, still there may be seen, in general, dark curved bars passing over the field, which exhibit an indistinct rotary movement. As has already been mentioned (p. 84), this affords means of distinguishing a biaxial mineral from a uniaxial one. But the passage of black bars nearly parallel to themselves is not always sufficient to establish the uniaxial character of the mineral. In fact, when the angle of the optic axes is not very large, and the acute bisectrix makes a large angle with the axis of the microscope, the dark arms of the hyperbolas which are seen to pass over the field can easily be confounded with right lines. The dark line of the optic axis is slightly curved at the extremities in opposite directions, but such curvature is usually not observable. It is straight only when the axial angle is 90 degrees.

EN RÉSUMÉ. When the black curves form a cross at the centre of the field of the microscope, the thin section is perpendicular to one of the three axes X, Y or Z. When perpendicular to Y it is dim and sometimes almost invisible.

When one arm of the black cross coincides at a given moment of rotation with one of the threads of the ocular, the thin section is perpendicular to a plane containing two of the axes X, Y, Z. In this case different appearances are to be noted.

1. The section is perpendicular to the plane X, Z, containing the optic axes, and its normal falls between the acute bisectrix and one of the optic axes. The figure presents no difficulty of interpretation. The formation and the curved outlines of the hyperbolas are distinct; when the dark bar coincides with one of the threads of the ocular (principal planes of the nicols) it marks the trace of the plane of the optic axes. It is possible to distinguish very clearly the side of the optic axis round which the dark bar turns, from the side of the bisectrix. It is possible hence, to note the place of the other quadrants as defined by the branches of the dark cross, and the mica-plate permits the determination of the sign of the nearest bisectrix, which is the sign of the mineral.

2. The plate is still perpendicular to the plane X, Z, but its normal falls in the obtuse angle of the axes. The appearances are analogous to those of the preceding case; but if the angle of the optic axes (round the acute bisectrix) is small, all the dark bars will cross the centre of the field of the microscope without apparent curvature; and this is especially true of that bar parallel with the optic plane. In this case it becomes difficult to determine

the direction of the axial plane, and consequently the orientation of the thin section.

3. The section is perpendicular to one of the planes (X, Y), (Y, Z). It is easy to see that in this double case, the dark bar once centred is perpendicular to the trace of the optic plane. When the locus of the bisectrix is near the border of the field, the dark curve is distinctly bent by rotation of the stage of the microscope, and reveals the direction of the optic plane.

But if the field be withdrawn in the direction toward Y, the dark bar becomes faint, and remains practically parallel with itself.

Sections perpendicular to Y, that is to say, parallel to the plane of the optic axes, present a general diffusion of darkness, at the positions of extinction in parallel polarized light, but on rotation indistinct hyperbolas go out from the centre rapidly.

The mica-plate, inserted at 45° with the black cross of an acute bisectrix of a biaxial crystal, gives usually similar appearances and indications as with uniaxial crystals. If it does not and if the sign of this bisectrix be unknown, it can be determined by comparing the axis Y in the plate with the other axis in the plate by the use of the quartz plate in parallel polarized light (p. 65). The same process would be necessary in the case of a section perpendicular to the obtuse bisectrix; in fact, the trace of the plane of the optic axes, is of a sign contrary to that of the bisectrix perpendicular to the section.

Colored curves of interference figures formed by equal retardation of light appear in thin sections only when the mineral is highly doubly refracting or when the section is very thick, and most frequently the colors seen belong to the curves nearest the centre, corresponding to one, two or three wave-lengths of retardation.

The position of the plane of the optic axes often affords the determination of a doubtful section; thus in certain minerals the axial plane is constantly perpendicular to the favorite direction of elongation. Such is the case with epidote (elongation parallel to the edge 001 : 100, plane of the axes 010), or wollastonite (same as in epidote). The contrary case is afforded by augite, amphibole, enstatite and hypersthene, whose elongation is parallel to the axial plane.

## THE MONOCLINIC SYSTEM AND POLARIZED LIGHT.

The phenomena of crystals of the monoclinic system in polarized light are similar to the same in the orthorhombic system, and the same terms are used. The two systems differ only in the manner of dispersion of the optic axes, and in the relative positions of the axes of ether vibration with respect to the crystallographic axes (p. 70).

Extinction angle. One of the axes of ether vibration (frequently Y) coincides with the ortho-diagonal crystallographic axis *b*, which is the axis of symmetry of the system (p. 20); and the other two are in the plane of symmetry; that is to say, they lie in a plane parallel to the clinopinacoid (010). The angles made by these two axes of ether vibration with the crystallographic axes in the same plane are called ***extinction angles***, and afford a means of distinguishing monoclinic crystals in polarized light.

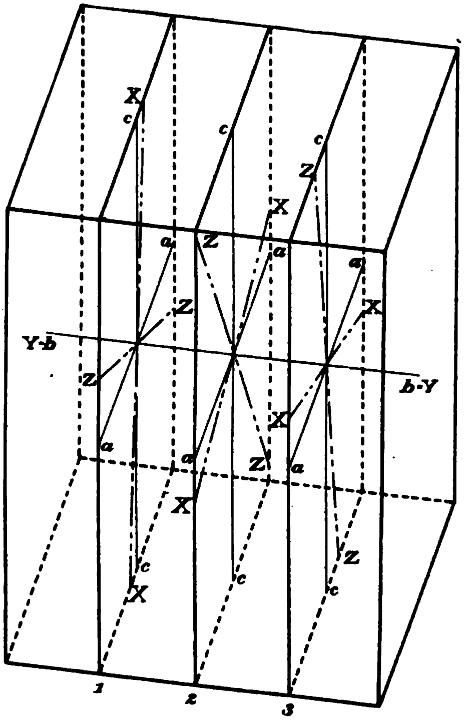

Fig. 79.

**A single Monoclinic Crystal in conventional position, showing the Plane of Symmetry and the Axes X, Y, and Z, for Epidote (1), Diopside (2) and Glaucophane (3).**

Let figure 79 represent a simple monoclinic form in its conventional position. The full lines represent the directions of the crystallographic axes *a, b, c.* The three planes represented between the pinacoids 010 and $0\bar{1}0$ are intended to show the plane of symmetry, and the dotted lines lying in them, three possible positions of the axes of ether vibration for different minerals, with respect to the axes *a* and *c*. The axes of ether vibration are necessarily at right angles to one another, in the same mineral, and bisect the respective optic angles. The optic axes are not represented. In the figure Y coincides with *b*, but in many minerals X or Z coincides with *b*. The first symmetry plane (1) represents the condition actually found in epidote. The second (2) represents diopside, and the third (3) glaucophane.

Dispersion in the monoclinic system. In the monoclinic system not only may the loci of the optic axes for the different colors be different in the same crystal, but the locus of the bisectrix may, in certain conditions, be different for the different colors. There are three cases:

*Inclined dispersion* takes place when the optic normal (Y) coincides with the crystallographic axis *b*, and the optic plane is in the position represented by fig. 79. It is seen in gypsum and augite. In this case the bisectrix emerges, for the violet rays, at some distance to the right or left from the point of emergence of the bisectrix for the red rays, but in the trace of the axial plane; and at the same time the dark rings, seen alternately in red and blue light, (p. 82) shift their positions in the same directions, becoming also larger or smaller. If $\rho < v$, as in fig. 80, the innermost dark ring for red light may be represented by the small circles, and the bisectrix would be intermediate, at *R*; for violet light the bisectrix is removed to *V*, and the innermost dark rings are seen as represented by the larger circles. Both bisectrices are subject to this dispersion.

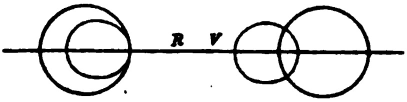

Fig. 80. Inclined Dispersion

In inclined dispersion, in white light, there is a difference in distribution of colors surrounding the loci of the optic axes, owing to the different superposition of the colors after dispersion. One set of rings may be larger than the other, or more elliptical. In the diagonal position of the section there is no constancy in the positions of the colors relative to the sides of the hyperbolas; one hyperbola may have its concave side fringed with blue and the other with red. If the dispersion of the bisectrix be not large the dark hyperbolas will be symmetrically colored on their concave sides in a manner similar to that of rhombic dispersion (p. 81).

Obviously the plane of symmetry of the colors of the interference figure in inclined dispersion contains the long axis of the figure itself.

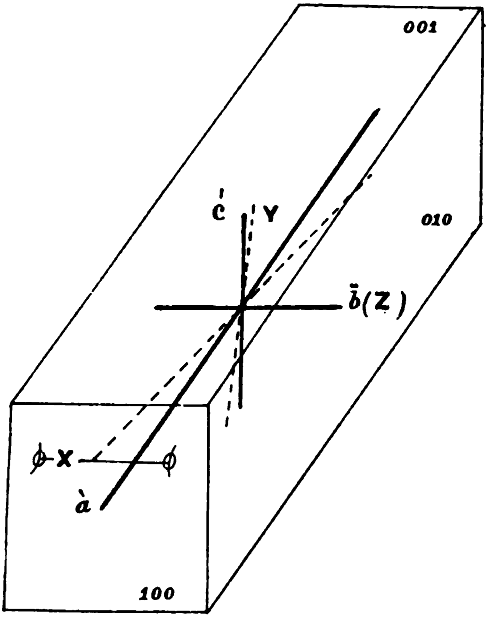

Fig 81. Position of the Optic Plane in Horizontal Dispersion

*Horizontal dispersion* takes place in the interference figure when the obtuse bisectrix coincides with the crystallographic axis

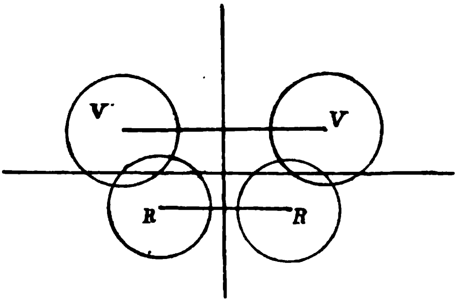

Fig. 82. Horizontal Dispersion.

*b* (fig. 81). In this case the other bisectrix and the optic normal are in the plane of symmetry, at right angles to *b*. The optic plane is perpendicular to the plane of symmetry. The obtuse bisectrix is not horizontally dispersed, but shows crossed dispersion. The acute bisectrix and the optic normal are horizontally dispersed. Normal orthoclase exhibits horizontal dispersion. The positions of the acute bisectrix and of the dark rings for red and blue light are shown in fig. 82, which represents $\rho < v$.

When this interference figure is seen in white light the colors that appear about the loci of the optic axes are dispersed horizontally, i. e., uniformly in a direction perpendicular to the long axis of the figure. The distribution of the colors is the same in quadrants on the same side of that axis. The plane of symmetry, therefore, for these colors is perpendicular to the long axis of the figure.

*Crossed dispersion* is seen in those monoclinic minerals in which the acute bisectrix coincides with the crystallographic axis *b*. Then the obtuse bisectrix and the optic normal are in the plane of symmetry, where they may occupy any positions. Crossed dispersion is exhibited by borax. The obtuse bisectrix and the optic normal are horizontally dispersed, and the centre of the interference figure about the acute bisectrix is the same for all colors, but the distribution of the colors about the centre is more or less oblique to the trace of the axial plane.

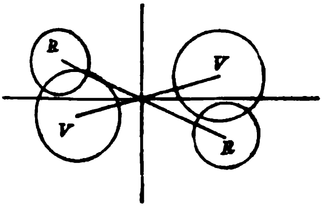

Fig. 83. Crossed Dispersion.

The positions of the dark rings, seen in red and blue light alternately, may be represented as in figure 44 in which $\rho > v$.

When this interference figure is seen in white light the colors that appear about the loci of the optic axes are dispersed obliquely, tending to occupy the opposite quadrants. In one of the optic loci the colors alternate from N E to S W, and in the opposite direction in the other, the degree of obliquity with the axial plane depending on the relative positions of the axes for the red and the blue rays, and the consequently variable superposition of the different phases. The two axial figures, however, are equally illuminated, and appear of the same size. That color which has the less dispersion appears near the bisectrix, within the innermost colored ring, in greater force than its complementary color. and occupies the same side of the trace of the axial plane in the two axial figures. In the diagonal position this color also fringes the concave sides of the hyperbolas, but alternates obliquely with its complementary color.

The different kinds of dispersion of the interference figure may be summarily expressed, as follows:

| *System* | *Dispersion* | *Colors are Symmetrical to* |
|---|---|---|
| **Orthorhombic** | **Rhombic, fig. 34** | **Both planes** |
| **Monoclinic** | **Inclined, fig. 41** | **The optic plane** |
| | **Horizontal, fig. 43** | **The plane perpendicular to the optic plane** |
| | **Crossed, fig. 44** | **The locus of the bisectrix** |
| **Triclinic** | **Combinations (p. 92)** | **Asymmetrical** |

By optical characters alone it is sometimes very difficult to distinguish minerals of the monoclinic system from those of the orthorhombic and hexagonal systems. Resort must then be had to chemical or to other structural features. The axial interference figure of biotite, for instance, remains a black cross, on rotation, as in uniaxial minerals.

## THE TRICLINIC SYSTEM AND POLARIZED LIGHT.

The fact that minerals of the triclinic system have no symmetry, except about a point renders it impossible to state any general definitive principles respecting their phenomena. In polarized light each mineral has its own characters, a circumstance which renders their determination direct and unique.

The axes of ether vibration have no fixed relation to the crystallographic axes. The optic axes and the axes X, Y, Z are subject to dispersion, though so small or so confused that in most instances it can be neglected. Rarely an axis of ether vibration coincides, nearly or quite, (as in oligoclase) with a crystallographic axis.

Triclinic crystals manifest all the phenomena, already described, seen in monoclinic crystals, such as polarization, double refraction, quadruple extinction and chromatic interference figures.

Dispersion in the triclinic system produces a colored interference figure which always is made up of the superposition of several kinds of dispersion, and is valueless except to fix the mineral in the triclinic system. It has no symmetry.

## IMPORTANT CHARACTERS COMMON TO ALL THE CRYSTALLOGRAPHIC SYSTEMS.

ELONGATION AND FLATTENING. In the microscopic examination of minerals in polarized light, it becomes necessary to compare the directions of extinction with their cleavages or with their known edges. Crystals have characteristic tendencies to elongation parallel with certain edges, or of flattening parallel with certain pinacoids, or less commonly other faces, or of twinning on certain faces. These hence become important data for comparison with the directions of the optical phenomena. Experience and theory both show that these favorite directions are those whose symbols are the most simple. Thus, flattening takes place, as in mica and in tridymite, parallel to the basal plane (001), and in certain feldspars parallel to the brachypinacoid (010). Elongation takes place, as in apatite, amphibole and pyroxene, parallel to the intersection of the faces of the prism, parallel to the intersection of 110 and 100 as in zircon, rutile and wernerite; parallel to the edge 001 : 100 in epidote and wollastonite; parallel to the edge 001: 010 in the feldspars and to 100: 010 in cyanite, etc.

In general it might be stated that, in the tetragonal and hexagonal systems flattening takes place perpendicular to the vertical axis; if not, then the elongation is parallel to it. Consequently the extinctions in the interesting zones are found constantly parallel to the length, and in certain cases, exactly parallel to the trace of the easy cleavage. In fact, when the single easy cleavage, as in the micas, is practically perpendicular to the vertical axis the trace of the cleavage is practically parallel to the direction of extinction, whatever be the orientation of the section.*

In the orthorhombic system the flattening is perpendicular, or the elongation is parallel to one of the three crystallographic axes, and the extinctions in elongated sections are hence parallel to the elongation.

The monoclinic system presents a favorite elongation parallel to the axis *b* or parallel to one of the principal edges contained in the clinopinacoid or plane of symmetry. In the former case extinctions are longitudinal. In the second they vary according to the position of the axes of ether vibration with respect to the elongation. The angle of maximum extinction of different sections in the zone perpendicular to the plane of symmetry measured on the constant direction of the edge of favorite elongation, may then become a characteristic of the mineral studied. Such is the case with amphibole, pyroxene and orthoclase. It is well to note that this elongation is here embraced in one of the planes containing two of the axes X, Y, Z, which simplifies considerably the theoretical search for this maximum extinction.

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* The micas are strictly monoclinic and rigorous parallelism does not occur. Their symmetry, however, is so nearly that of hexagonal crystals that they furnish an excellent practical example.

Finally, in the triclinic system, the elongation may be in any direction with respect to the axes X, Y, Z, and the question becomes one of wide limits. Yet, in some special cases, the edge of elongation is still very near a plane containing two axes of ether vibration thus affording extinction practically parallel with the elongation in all sections perpendicular to the plane. Such is, for instance, the edge 100: 010 in cyanite and 001 : 010 in a part of the triclinic feldspars.

CLEAVAGES. In the isometric system cleavages are parallel to the faces of the cube as in perovskite, analcite, or of the octahedron as in fluorite, or of the dodecahedron as in sodalite. In other cubic rock-forming minerals it is wanting, or not noticeable in thin sections.

In the tetragonal system usual cleavage is either parallel to the vertical axis or perpendicular to it. In the former case more or less regular quadratic or octagonal outlines appear, depending on the inclination of the section to the vertical axis. There may be two systems of cleavage intersecting each other at uniform angles. If the section be perpendicular to *c* extinctions take place parallel to the prismatic cleavages, and a basal cleavage is invisible. For oblique sections the vertical cleavages form a variable angle with the extinctions, but the basal cleavage is parallel with it. Sometimes a cleavage is parallel to the face of the unit pyramid, as one of the cleavages in zircon. In such a case extinction is usually oblique to the cleavage.

In hexagonal crystals sections perpendicular to *c* have hexagonal or triangular cleavage directions, unless the cleavage be parallel to 0001, in which case it is not apparent. In sections parallel to *c* prismatic cleavages will be parallel to each other and perpendicular to the basal cleavage. In this case extinction is always parallel to the cleavages. In other sections cleavage cracks appear which are parallel to or intersect each other, the angle depending on the inclination of the section to the axis *c*, and the extinction angle on the prismatic cleavages is equally variable.

Crystals belonging to the orthorhombic system are likely to show pinacoidal or prismatic cleavages running in parallel cracks in all sections parallel to *c*. These cleavages intersect when the section is inclined to the principal axis. They are all parallel to each other when the section is parallel to the axis *c*, and the pinacoidal at right angles when perpendicular to *c;* the prismatic cleavages form a system of angles not 90°. Pyramidal cleavages appear in angular figures whose forms depend upon the inclination of the section to the pyramidal planes.

In the monoclinic system "sections of regularly developed crystals, and the figures made by the cleavage cracks are symmetrical only when they belong to the orthodiagonal zone. The cleavage is either single (parallel to pinacoids or orthodomes) and lies in the plane of symmetry, or stands at right angles to it; or the cleavage is the same parallel to two faces (prismatic) which make equal angles with the plane of symmetry. A single cleavage gives a single system of parallel cleavage cracks, in all sections but those parallel to the cleavage face. Two single cleavages occurring in the same crystal cannot be equal; they furnish parallel cleavage cracks in all sections in the zone of the cleavages, and intersecting systems of dissimilar cleavage cracks in all other sections." (Rosenbusch).

In the monoclinic feldspars are two important cleavages, one parallel to 010 and the other to 001, the latter being more marked. In thin sections they are usually both visible, but if the section be rather thick, that cleavage parallel to 010 is sometimes invisible. In sections parallel to 010 the basal cleavage is visible as straight parallel cracks; in those parallel to 001 the clinopinacoidal cleavage is seen in the same manner. In sections parallel to 100 both cleavages are visible, intersecting each other at right angles. The same is true for all sections parallel to the edge 001 : 100. In sections parallel to the edge 100 : 010 these cleavages form an angle which decreases from 90° to agreement with the supplement of the angle $\beta$ (64° ±).

A parting (p. 37) in sanidine is sometimes present parallel to 100, which might be mistaken for a cleavage parallel to 001 or to 010. It appears in thick sections. The true cleavage is seen in thinner sections. A coarser zonal structure is also sometimes very marked.

Minerals of the triclinic system "afford sections unsymmetrical in all zones. The same is true of all figures produced by intersecting cleavages. Each cleavage is parallel to only one face; hence there are no equivalent cleavage cracks which intersect one another. Cleavage cracks which intersect always belong to crystallographically dissimilar faces. In general those faces parallel to which there is cleavage are made the pinacoids." (Rosenbusch).

In the triclinic feldspars the usual cleavages are parallel to 001 and 010.

Twinning. When crystals are twinned the individual parts are attached to each other by a *composition face,* and one part is turned usually 180 degrees from agreement with the other part, about a *twinning axis* that is perpendicular to the *twinning plane.* Crystals thus grouped are called *twins,* but crystals repeated alongside of each other and not reversed constitute *grouping,* or parallel growths. The twinning axis is usually a crystallographic axis, or may be a line normal to a crystal face. The composition face though usually perpendicular to the twinning axis, is sometimes parallel to it, and sometimes is irregular owing to the mutual interpenetration of the twins, caused by cotemporary growth. If twins are simply adherent by the composition face they are *contact twins.* If they penetrate each other they are likely to have an irregular composition face and are called *penetration twins.* A *twinned plane* is one that is repeated and adjacent to its homologous plane of the other part of the crystal.

Although in each individual of a twinned crystal the optical characters are the same, and identical with the same characters in a simple crystal, and hence are amenable to the principles already given, yet there are certain forms of twinning so fine as to be visible only with the aid of the microscope, and others that constitute diagnostic characters for the determination of mineral species. A knowledge of the forms of habitual twinning becomes therefore, a powerful aid to the microscopist, and especially in the study of the feldspars. The most important types of twinning in the feldspars are the Carlsbad, Baveno, Manebach, albite and pericline.

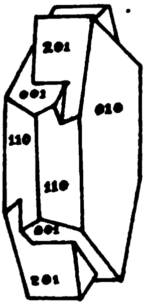


Fig. 84.
Carlsbad Inter-penetrating Twins.

*Carlsbad twinning.* The most simple of these important forms of twinning is that known as the Carlsbad type. It occurs in the monoclinic as well as in the triclinic feldspars. Carlsbad twins may be again twinned according to the albite or the pericline types, and when their extinctions are parallel, as often happens, confusion may result unless they be separately recognized.

Figure 84 represents the usual aspect of a simple Carlsbad twin crystal of orthoclase. The twinned plane is 110, but with the obliteration of

100, and the contact faces are 010. It appears as if after the orientation of two crystals of the same form they had united, but with their homologous ends in opposite directions. and had continued to grow after union. It is not always that the twins are of equal size, but two or more small individuals may be twinned with a single larger one, the small crystals being apparently cemented on the larger crystal. In the Carlsbad form the twins are supposed to be turned 180° about the vertical axis *c*, or about a line perpendicular to the face 100. A thin section through such a crystal in the zone parallel to the axis *b* would evidently consist of two parts whose basal cleavages would be parallel, and whose extinctions would be simultaneous. The traces of the optic planes in the two portions would be found parallel.

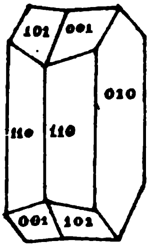


Fig. 85.
Carlsbad Twins without Inter-penetration.

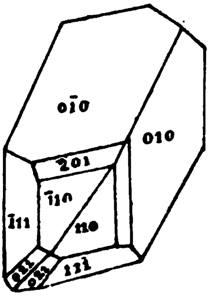


Fig. 86.
Baveno Twins of Orthoclase.

Figure 85 represents a Carlsbad twin crystal without penetration, the faces 101 and 001 being so nearly in the same plane as to appear to be one plane. The face 100, which is very rarely seen, is here obliterated by the prismatic faces 110, and the elongation is parallel to the prism edges. Sometimes a Carlsbad twin consists of two parts elongated parallel with the clinodiagonal axis, the vertical axis being relatively shortened.

Figure 86 represents a *Baveno twin* of orthoclase, the form being elongated parallel to *a*. Here the twinning plane is the clinodome 021, to which the twinning axis is normal, and the composition face is also 021. The clinopinacoids and basal planes unite to constitute a nearly square prism, in which cleavage is parallel to each side, and the optic planes stand at right angles to each other. This type is not common.

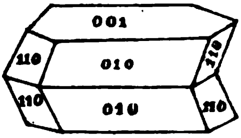


Fig. 87.
Manebach Twin of Orthoclase

The rarest type of twinned orthoclase is the *Manebach* twin, the composition face being here the base 001, represented by figure 87. The axis of revolution is perpendicular to the base 001; cleavage is sufficient to distinguish the parts, since that which is easiest in one is parallel to the same in the other, and the cleavage parallel to the clinopinacoid, in one is continuous into or at least parallel with the same in the other.

While these forms prevail in the monoclinic feldspars it is not uncommon that they unite in the triclinic feldspars, with the albite and pericline types of twinning, which are rarely absent in the latter.

*Albite and Pericline Twinning.* All the plagioclastic feldspars are characterized by fine *polysynthetic twinning,* which produces a fine superficial striation generally visible to the naked eye; it is caused by a succession of changes in direction of growth of the crystal, the angle between adjacent striation faces being about 172°. When the twinning axis is a normal to 010 this twinning forms the *albite type.* When it is parallel to *b* it forms the *pericline type.* In the albite type the lamellæ are parallel to 010 and produce striations on the sides 001 and 100. They are invisible in thin sections parallel to 010, but in all others they are apparent in narrow bands which polarize and extinguish alternately, on being rotated between crossed nicols, the bands being parallel to the brachypinacoidal cleavage. The external pericline striations are visible on all faces of the crystal as below except in andesine. If striations appear on the face 010 they are necessarily of the pericline type. In thin sections, if the pericline twinning exists, it is visible in sections cut in all directions, except parallel to the composition face. The composition face is the *rhombic section,* so-called, i. e.. a plane perpendicular to 010 and cutting the faces 110 and $1\bar{1}0$ in such a position as to make sections on 010 and 110 and $1\bar{1}0$ that have internal angles equal to each other (figure 88.). In andesine the rhombic section is practically parallel to the base, 001.

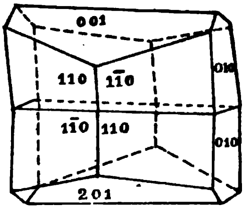


Fig. 88.
Pericline Twin of Albite.

Figures 89 and 90 represent each a pair of microlitic twins of the albite type, the former having an elongation parallel to the axis *a,* and the latter a flattening parallel to 010.

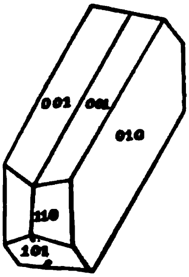


Fig. 89.
**Microlitic Albite Twins, showing Elongation parallel to the Axis *a*.**

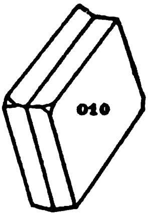


Fig. 90.
**Microlitic Albite Twins, flattened parallel to 010.**

Figure 91 represents a triclinic feldspar included between the principal crystal faces 001, 100 and 010. The lines which cross each other on the faces 001 and 100 indicate the external striations due to the albite and pericline types of polysynthetic twinning; those that appear on the face 010 represent the external striations due to pericline twinning. In the various plagioclases the latter make different angles with the basal cleavage or with the edge 001 : 010. In albite it is about as shown in the figure; viz. 18° to 22°; in oligoclase it is 6°; in andesine it is 0°; in labradorite from 2° to 9° in the opposite direction, and for anorthite it is 18° in the same direction as for labradorite.

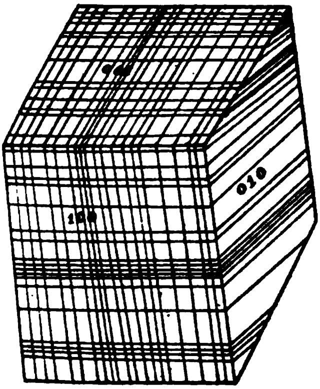


Fig. 91.
**Triclinic feldspar form showing the positions of the characteristic Albite and Pericline Striations.**

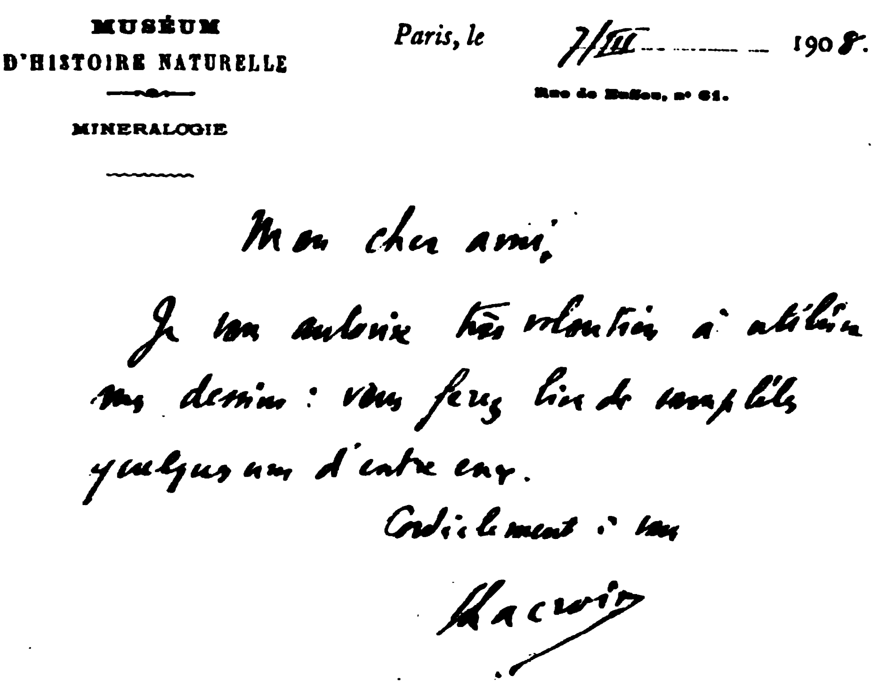
When the polysynthetic twinning, albite or pericline, is again enveloped by a Carlsbad twinning, a thin section manifests it by the occurrence of two pairs of bands on one side, which extinguish or polarize in sympathetic alternation, differently from two pairs of bands on the other side. Generally the darkened line which separates the Carlsbads can be seen. It is heavier than the other dark lines, and is apt not to agree with them strictly in direction, or to be otherwise irregular.

Extinction Angles are measured from some plane containing an axis of ether vibration to some visible crystallographic character, such as cleavage, parting, elongation, crystal edge or twinning plane.

Uniaxial minerals and those of the orthorhombic system generally show extinction parallel to at least one crystallographic feature.

Monoclinic crystals give oblique extinction in all sections except those of the zone perpendicular to the plane of symmetry.

Triclinic crystals give oblique extinction in all sections.



**MUSÉUM**
**D'HISTOIRE NATURELLE**

**MINERALOGIE**

Rue de Buffon, n° 61.

Paris, le 7/III 1908.

Mon cher ami,

Je vous autorise très volontiers à utiliser mes dessins : vous ferez bien de compléter quelques uns d'entre eux.

Cordialement à vous

A Lacroix

# PART II.

## DESCRIPTION OF MINERALS.

INTRODUCTION. The minerals are arranged in alphabetical order, so far as practicable. Many minerals, which belong in natural groups characterized by similar chemical and physical characters, are described to better advantage by consideration of the group as a whole. In such cases they are to be found by referring to the group name in its alphabetical position. Varieties, and some rare and imperfectly known minerals, are briefly described in connection with the more important species to which they are related. As an additional guide cross references are introduced.

The description of each mineral is given in the following order:

Name.

Crystal system (and axial ratio).

Chemical composition (COMP.), usually expressed merely be a formula.

Physical characters (PHYS. CHAR.), including crystal habit, twinning, cleavage, hardness (H), specific gravity (G), pyrognostic characters, and solubility.

Optic properties (OPT. PROP.), including optic orientation, refringence, birefringence, sign, optic angle, dispersion, color, pleochroism, and absorption.

Inclusions (INCL.).

Alterations (ALTER.).

Occurrence (OCCUR.).

Diagnostics (DIAG.).

In the description of each group of minerals the order adopted is essentially the same as that outlined above, with the addition of:

Classification (CLASS.).

**ACMITE,** see pyroxene group. **ACTINOLITE,** see amphibole group. **ADAMITE,** see olivenite. **ADELITE,** see wagnerite. **ÆNIGMATITE,** see amphibole group. **ÆRINITE,** see chlorite group. **ALBITE,** see feldspar group. **ALLACTITE,** see flinkite. **ALLANITE,** see epidote group. **ALMANDITE,** see garnet group.

## ALUNITE.

RHOMBOHEDRAL $c = 1.252$ $K_2Al_6S_4O_{22}+6H_2O$

PHYS. CHAR. Crystals rhombohedral, sometimes resembling cubes; often fibrous to lamellar. Very easy cleavage || 0001. Sometimes much flattened parallel to the base. G. = 2.58 to 2.75. H. = 3.5 to 4. Infusible. Soluble in $H_2SO_4$.

OPT. PROP. Uniaxial; positive. The flattening parallel to the base produces an apparent elongation in vertical sections which is negative, and shows parallel extinction. Colorless.

$$n_g = 1.592 \quad n_p = 1.572$$
$$n_g - n_p = 0.018 - 0.020$$

OCCUR. Alunite is found in rhombohedrons often bordered with opaque inclusions, or in lamellar masses, as an alteration product of acid volcanic rocks by means of sulphurous vapors. Also probably sometimes produced by the action of sulphated meteoric waters upon feldspathic rocks.

DIAG. Differs from brucite in occurrence and association; also has inferior cleavage and non-flexible lamellæ. Distinguished from sericite by the sign of the elongation (or direction of lamination).

**AMARANTITE,** see copiapite.

## AMBLYGONITE.

TRICLINIC $a:b:c::0.245:1:0.461$ $(Li,Na)[Al(F,OH)]PO_4$
$\alpha = 68° 47'$ $\beta = 98° 44'$ $\gamma = 85° 52'$

PHYS. CHAR. Crystals coarse, indistinct. Easy cleavages || 001, and $1\bar{1}0$.[1] Polysynthetic twinning common in two directions nearly at right angles in sections ⊥ 001 and 110. The composition faces nearly bisect the angles between the easy cleavages. Soluble in $H_2SO_4$.

OPT. PROP. The axis X coincides very nearly with the direction of the intersection of 001 and $1\bar{1}0$. The plane containing Y and X makes an angle of 23° with 001 in the obtuse angle $001 \wedge 1\bar{1}0$ measured in a section normal to 001 and $1\bar{1}0$. Dispersion of the axes weak with $\rho > v$. Inclined dispersion distinct and crossed dispersion strong.

---

[1] **Dana adopts another fundamental form. His 001 = 001, 100 = $\bar{1}10$, and $\bar{1}10$ = $\bar{1}\bar{1}0$.**

$$(-)\ 2V = 50°\text{-}55°$$
$$n_g = 1.597\ n_m = 1.593\ n_p = 1.578$$
$$n_g - n_p = 0.019$$

Color white, or of pale tint. Streak white. Colorless in thin section.

OCCUR. Found in pegmatite dikes, coarse albite granites, etc. Rare. Large liquid inclusions are numerous.

**Montebrazite** or **hebronite** is like amblygonite, but contains more hydroxyl and less sodium. The optic plane occupies the position of the plane (in amblygonite) containing X and Y. The dispersion of the axes is weak with $\rho < v$; horizontal and inclined dispersion also weak.

$$(-)\ 2V = 50°\text{-}90°$$
$$n_g = 1.620\ n_m = 1.611\ n_p = 1.600$$
$$n_g - n_p = 0.020$$

**Durangite** $\{ Na[(Al,Fe)F]AsO_4 \}$ is chemically related to amblygonite, but it is monoclinic with $a:b:c::0.772:1:0.825$ and $\beta = 64°\ 47'$; crystals pyramidal. Cleavage distinct || 110. Color orange-red; colorless to pale yellow in thin section. H. = 5. G. = 4. Fusible at 2. Decomposed by $H_2SO_4$. Optically negative; the plane of the optic axes is normal to 010; $X \wedge c = -25°$. Optic angle large. $2H = 80°\ 49'$ Na; axial dispersion weak, $\rho > v$; horizontal dispersion distinct. Very rare. Found in a tin mine.

DIAG. Amblygonite is characterized by moderate relief and birefringence, asymmetrical extinctions, two good cleavages, and frequent polysynthetic twinning in two directions.

### Amphibole Group.

The minerals of the amphibole group are orthorhombic, monoclinic, and triclinic silicates of magnesium, calcium, iron, or sodium, with aluminum or ferric iron in some cases.

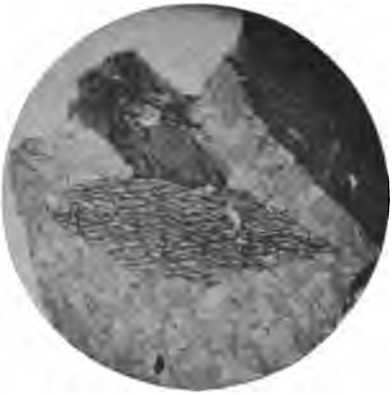


Fig. 1. Basal section of amphibole showing prismatic cleavages and crystal outline. U. W. 598. One nicol. × 15.

Phys. Char. Crystals prismatic usually elongated parallel to $c$. Very marked and regular cleavages parallel to the prism faces 110 and 1$\bar{1}$0. Cleavage angle varies little from 124° in all species except ænigmatite in which it is 114°. Twinning common || 100, sometimes multiple. G. = 2.9 - 3.55. H. = 4.-6.5. Fusible at 4 - 6. Insoluble in acids, except slowly in HF.

Opt. Prop. The optic plane is parallel to 010 in the orthorhombic and monoclinic amphiboles, and varies only slightly from the same position in the triclinic. In the monoclinic amphiboles the axis Z makes an angle with the vertical crystallographic axis which varies from 0° to 22° except in the uncommon species that are rich in sodium (e. g. arfvedsonite). The elongation is

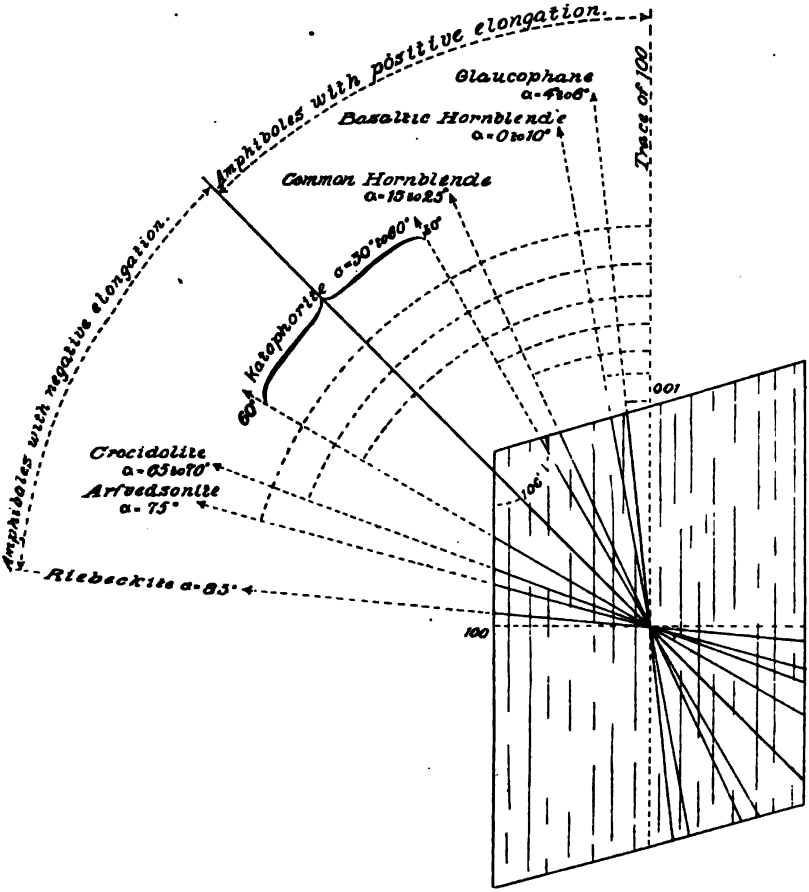


Fig. 2. Diagram of extinction angles in aluminous monoclinic amphiboles in sections parallel to 010. The angle between Z and $c$ is called $a$.

therefore positive in the common species. See figure 2. The average refringence is less than that of the pyroxenes; it increases with the increase of iron. The birefringence of the common varieties is about 0.020 to 0.025, but in grünerite and ferriferous hornblende it is much more. Amphiboles in thin section are green, brown, yellow, blue, or colorless. Pleochroism is usually distinct, and is intense in the ferriferous varieties. In the common varieties the absorption is greatest parallel to Z and least parallel to X.

ALTER. Amphiboles alter readily to chlorite, biotite, serpentine, epidote, calcite, talc, etc. The alteration to chlorite, biotite, serpentine, or talc is a gradual process, usually beginning along the edges and the cleavages of the amphibole, and sometimes continuing until no trace of the original mineral, except perhaps its form, is to be found. Under the action of intense heat, as, for instance, when fragments of amphibole crystals are caught in volcanic rocks, the mineral is often rounded, corroded, and more or less fused. Upon cooling the amphibole does not recrystallize; in its place appear grains of magnetite, microlites of augite, or an aggregate of these two minerals.

OCCUR. Amphiboles are found in all classes of eruptive, and in many metamorphic, rocks. In some cases they are sufficiently abundant to constitute rocks, with other minerals so subordinate in amount as to be merely accessory. Amphiboles are often formed by the alteration of pyroxenes.

DIAG. Amphiboles are to be distinguished from pyroxenes thus:—

| Amphiboles. | Pyroxenes. |
|---|---|
| Cleavage angle about 124°. | Cleavage angle about 93°. |
| Crystals usually long prismatic. | Crystals usually short prismatic. |
| Color and pleochroism usually marked. | Color and pleochroism usually weak. |
| Maximum extinction angle 0°-25° (except arfvedsonite, etc., which have marked pleochroism in blue, green, and yellow tints.) | Maximum extinction angle 0°-95° (common species 30°-54°) |
| Most species negative. | Most species positive. |
| Alter to chlorite, etc. | Alter to amphibole, etc. |

CLASS. The amphibole group includes the following species:

Orthorhombic

| | |
|---|---|
| Anthophyllite | $(Mg.Fe)SiO_3$ |
| Gedrite | $(Mg.Fe)SiO_3$ with $(Mg,Fe)Al_2SiO_6$ |

Monoclinic

| | | | |
|---|---|---|---|
| Non-aluminous amphiboles | | Tremolite | $CaMg_3(SiO_3)_4$ |
| | | Actinolite | $Ca(Mg,Fe)_3(SiO_3)_4$ |
| | | Richterite | $(K_2,Na_2,Mg,Ca,Mn)SiO_3$ |
| | | Cummingtonite | $(Fe,Mg)SiO_3$ |
| | | Grünerite | $FeSiO_3$ |
| Aluminous or ferriferous amphiboles | Hornblende | Edenite<br>Pargasite<br>Common hornblende<br>Basaltic hornblende<br>Barkivikite | $mCa(Mg,Fe)_3(SiO_3)_4$<br>$\pm n(Mg,Fe)_2(Al,Fe)_4Si_2O_{12}$<br>$\pm pNa_2Al_2(SiO_3)_4$ |
| | Katoforite | | |
| | Arfvedsonite | | $(Na_2,Ca,Fe)_4Si_4O_{12} + (Ca,Mg)_2(Al,Fe)_4Si_2O_{12}$ |
| | Riebeckite | | $2NaFe(SiO_3)_2.FeSiO_3$ |
| | Crocidolite | | $NaFe(SiO_3)_2.FeSiO_3$ |
| | Glaucophane | | $NaAl(SiO_3)_2.(Fe,Mg)SiO_3$ |

Triclinic

| | |
|---|---|
| Ænigmatite | $Na_4Fe_9(Al,Fe)_2(Si,Ti)_{12}O_{38}$ |

## ANTHOPHYLLITE.

ORTHORHOMBIC $a:b:c::0.5137:1:?$ $(Mg,Fe)SiO_3$

PHYS. CHAR. Crystals prismatic, rare. Commonly fibrous, long prismatic, or lamellar. Perfect prismatic cleavage at an angle of 125° ±. Cleavage or parting || 010 and 100 in traces. Occurs in regular growths with hornblende and biotite. G. = 3.1-3.2. H. = 5.5-6. Insoluble. Difficultly fusible.

OPT. PROP. The optic plane is parallel to 010; Z is parallel to the vertical axis, and the elongation is therefore positive, like the mineral itself. The extinction is always parallel. The angle of the optic axes is large and variable. Dispersion $\rho < v$.

$$(+)\ 2V = 84° \pm$$

$$n_g = 1.657 \quad n_m = 1.642 \quad n_p = 1.633$$

$$n_g - n_p = 0.025$$

Color brown to green. No pleochroism nor color in thin section. In thick section the pleochroism is as follows:—

Z = yellow or pale green
Y = brownish
X = brownish

ALTER. Anthophyllite alters rather readily to talc, bastite, etc.

OCCUR. Found in various schists, and also, as secondary product, in eruptive rocks.

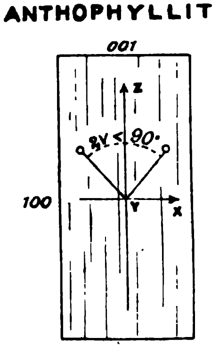


Fig. 3.
Optical orientation of anthophyllite.

DIAG. The orthorhombic amphiboles are easily distinguished from the monoclinic by their parallel extinction and absence of color.

## GEDRITE.

ORTHORHOMBIC $a:b:c::0.5229:1:0.217$ $(Mg,Fe)SiO_3$ with $(Mg,Fe)Al_2SiO_6$

Similar to anthophyllite, but contains alumina and more iron. Further it is negative, with $\rho > v$. The angle of the optic axes is large and variable.

$$(-)\ 2V = 78^\circ \pm$$

$$n_g = 1.644 \quad n_m = 1.636 \quad n_p = 1.623$$

$$n_g - n_p = 0.021 \text{ to } 0.023$$

Gedrite often contains inclusions of biotite, spinel, zircon, etc.; it sometimes contains inclusions like those giving the name to bronzite.

In chemical composition and in optical characters there is a gradation from anthophyllite to gedrite. As the alumina (or second molecule above) increases the optic angle about Z increases; when it passes 90° the sign changes. At the same time the refringence and birefringence decrease slightly.

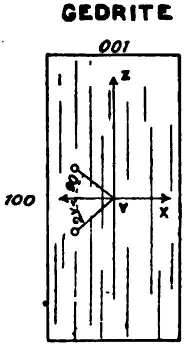


Fig. 4.
Optical orientation of gedrite.

## TREMOLITE.

MONOCLINIC $a:b:c::0.5415:1:0.2886$ $CaMg_3(SiO_3)_4$

$$\beta = 74^\circ\ 48'$$

PHYS. CHAR. Crystals long bladed or short prismatic; often acicular to fibrous. Perfect prismatic cleavage at an angle of 124° 11′; cleavage sometimes distinct || 100 and 010. Transverse fracture frequent. G. = 2.9-3.1. H. = 5.-6. Fuses to a white glass or gray mass. Insoluble in acids.

OPT. PROP. The plane of the optic axes is parallel to 010. The acute bisectrix is negative, making an angle of 72° to 74° with the vertical axis. The maximum extinction angle in the vertical zone is therefore 18°-16°. The elongation is positive. Dispersion, $\rho < v$, weak.

$$(-)\ 2V = 80^\circ \text{ to } 88^\circ$$

$$n_p = 1.6340 \quad n_m = 1.6233 \quad n_p = 1.6065$$

$$n_g - n_p = 0.0275$$

Colorless, white, gray or yellow. Colorless in thin section.

INCL. Tremolite of the metamorphic rocks often contains inclusions of carbonaceous matter, or of biotite, which give it various colors.

ALTER. The alteration of tremolite

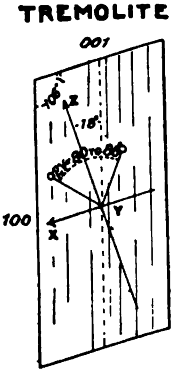


Fig. 5.
Optical orientation of tremolite.

to talc usually begins along the cleavage planes. It also alters sometimes to calcite.

Occur. It is found in schists, in veins, and in contact rocks; also in eruptive rocks as an alteration product.

*Asbestus* of commerce is a fibrous mineral which may be either tremolite, actinolite, or chrysotile; the best asbestus is a variety of chrysotile.

*Jade* is a tough compactly interlaced fibrous mineral, white to dark green in color, used by early man for ornaments. It is usually tremolite or actinolite; sometimes it is jadeite, one of the pyroxenes.

Diag. Tremolite is distinguished from hornblende by the absence of alumina and of color; also it has different etching figures on cleavage faces. Wollastonite has its optic plane perpendicular to its elongation, which is therefore of variable sign. Tremolite has the lowest index of refraction found in the monoclinic amphiboles.

## ACTINOLITE.

Monoclinic $a:b:c::0.5415:1:0.2886$ $Ca(Mg,Fe)_3(SiO_3)_4$

$\beta = 74° 48'$

Phys. Char. Similar to tremolite, but darker in color and higher in specific gravity on account of the presence of iron. G. = 3.1 to 3.2. Fusible to a gray enamel. Insoluble in acids.

Opt. Prop. Similar to tremolite, but the maximum extinction angle in the vertical zone is 15°, and the mineral is colored and pleochroic. Dispersion weak with $\rho < v$.

$(-)\ 2V = 75°$ to $80°$.

$n_g = 1.636 \quad n_m = 1.627 \quad n_p = 1.611$

$n_g - n_p = 0.025$

Color usually pale to dark green. In thin section the intensity of the color and of the pleochroism varies with the percentage of iron present. Tremolite contains less than three per cent. of FeO; actinolite varies in iron content from this amount to twenty per cent. or more. The pleochroic formula follows:—

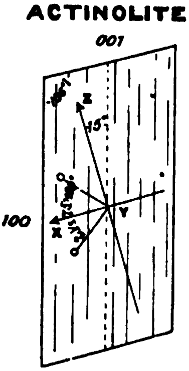


Fig. 6.
Optical orientation of actinolite.

Z = pale to dark green
Y = greenish yellow
X = very pale yellow

INCL. Similar to tremolite.

ALTER. Actinolite alters to chlorite, epidote, talc, etc.

OCCUR. Actinolite and tremolite have the same mode of occurrence and are often associated.

*Uralite* is a name given to amphibole which is produced by the alteration of pyroxene. It is usually actinolite, though it may also be tremolite, or even hornblende.

DIAG. Actinolite is distinguished from hornblende by the absence of alumina, and by different etching figures on cleavage faces. Epidote has its optic plane perpendicular to the cleavage.

## RICHTERITE.

MONOCLINIC $a:b:c::0.5499:1:0.2854$ $(K_2,Na_2,Mg,Ca,Mn)SiO_3$

$\beta = 75° 46'$

Similar to tremolite, but contains alkalies and manganese. G. = 2.8-3.1. The maximum extinction angle in the vertical zone is 17° to 20°. Optic angle large. Dispersion weak, $\rho < v$.

$$(-)\ 2V = 80°$$

$$n_g = 1.64\ n_m = 1.63\ n_p = 1.62$$

$$n_g - n_p = 0.024$$

Color brown to yellow; rarely rose red or blue to grayish violet. Pleochroism weak in thin section with Z yellowish brown, Y colorless, X pale yellowish.

Richterite occurs in rare alkaline rocks in Sweden. It is distinguished by its pleochroism, and by the presence of alkalies and manganese.

## CUMMINGTONITE.

MONOCLINIC $(Fe,Mg)SiO_3$

Identical with anthophyllite in composition and similar to actinolite in physical and optical characters. G. = 3.1-3.3.

OPT. PROP. Optic angle large. Dispersion $\rho < v$. The maximum extinction angle in the vertical zone ($Z \wedge c$) is + 14° to + 17°.

$$(-)\ 2V = 78° \pm$$

$$n_m = 1.638$$

$$n_g - n_p = 0.022 \pm$$

Cummingtonite is only slightly colored in thin section, and the pleochroism is weak.

Z = clear brownish yellow
Y = very pale yellowish
X = very pale yellowish

**Dannemorite** is like cummingtonite, but contains some manganese. It occurs in scales or needles. G. = 3.4. Difficultly fusible. Insoluble. The maximum extinction angle in the vertical zone is about 14°. Optic angle large; negative. Sometimes colorless; also colored and pleochroic in gray and yellow tints. Rare.

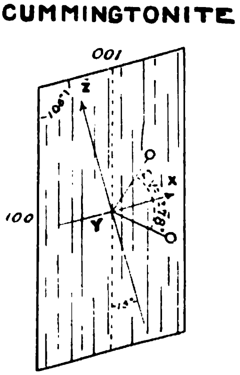


Fig. 7.
Optical orientation of cummingtonite.

Diag. Cummingtonite is distinguished from anthophyllite by its optical characters, and from actinolite by greater density and absence of calcium. It is rare.

## GRUENERITE.

Monoclinic $FeSiO_3$

Phys. Char. Crystals rare; usually in fibrous or lamellar masses. Perfect prismatic cleavage || 110. Twinning || 100 very polysynthetic. $G. = 3.7\pm$. Fusible to a black magnetic glass.

Opt. Prop. The optic plane is parallel to 010, and the negative acute bisectrix makes an angle of 75° to 79° with the vertical axis. The maximum extinction angle in the vertical zone is therefore 15° to 11°. The birefringence is the strongest known in the amphibole group with the single exception of the dark basaltic hornblende. The optic angle is large. Dispersion $\rho > v$, with weak inclined dispersion.

$$(-)\ 2V = 50^\circ \pm \ (2E = 95^\circ \pm)$$
$$n_m = 1.73$$
$$n_g - n_p = 0.056$$

Color brown. Luster silky. In thin section the pleochroism is weak with,

Z = pale yellow to brownish
Y = colorless
X = colorless

Occur. Found in micaschists in Europe; also in highly altered rocks of the Lake Superior region.

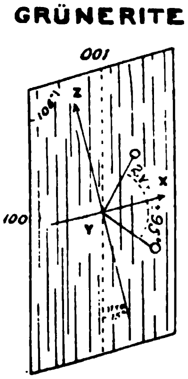


Fig. 8.
Optical orientation of grünerite.

Diag. Distinguished from other amphiboles by its strong birefringence and multiple twinning. But the birefringence is only 0.030 in one occurrence in the Lake Superior region according to Lane.

## HORNBLENDE.

Monoclinic $a:b:c::0.5509:1:0.2937$ $m Ca(Mg,Fe)_3(SiO_3)_4$
$\beta = 73^\circ\ 58'$ $\pm n(Mg,Fe)_2(Al,Fe)_4Si_2O_{12}$
$\pm p Na_2Al_2(SiO_3)_4$

Phys. Char. Usually elongated parallel to the vertical axis, sometimes in short well-formed crystals; also sometimes fibrous. Cleavage perfect || 110, making an angle of 124° 11′. Cleavage sometimes distinct || 100 and 010. Parting not infrequently present || 100 or 001, accompanied by polysynthetic twinning. The specific gravity varies from 3. to 3.47, increasing with the percentage of iron. Thus, for edenite, pargasite, and common hornblende, $G. = 3.$ to $3.1$, for basaltic hornblende, $G. = 3.1$ to $3.47$, and for barkevikite, $G. = 3.43$. $H. = 5.5$. Readily fusible to a greenish yellow or black enamel. Insoluble in acids.

Opt. Prop. The plane of the optic axes is parallel to 010, in which face Z makes a variable angle with the vertical crystallographic axis in the obtuse angle $\beta$; thus, it is 0° to 10° in basaltic hornblende, 12° to 14° in barkevikite, and 15° to 25° in common hornblende, pargasite, and some brown hornblendes.

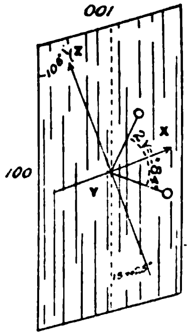


Fig. 9.
Optical orientation of common hornblende.

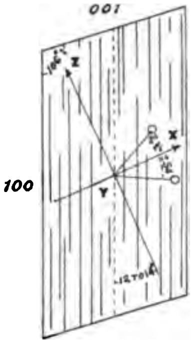


Fig. 10.
Optical orientation of barkevikite.

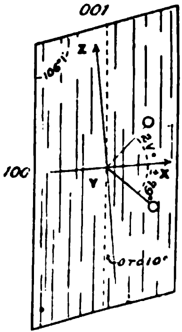


Fig. 11.
Optical orientation of basaltic hornblende.

The acute bisectrix is negative (X) in all varieties of hornblende, except *pargasite*, in which it is positive. The angle of the optic axes varies from 59° in pargasite to 84° in common hornblende. The refringence and birefringence vary together, increasing with the percentage of iron until in basaltic hornblende we have the strongest birefringence found in the amphibole group.

(—) $2V = 84°$ in common hornblende; extinction angle of 20°.
(—) $2V = 79°$ in basaltic hornblende; extinction angle = 1°-2°.
(+) $2V = 59°$ in pargasite; maximum extinction angle = 18°.

| | $n_g$ | $n_m$ | $n_p$ | $n_g - n_p$ |
|---|---|---|---|---|
| Pargasite | 1.632 | 1.620 | 1.613 | 0.019 |
| Common hornblende | 1.653 | 1.642 | 1.629 | 0.024 |
| Sorétite[1] | 1.683 | 1.673 | 1.661 | 0.022 |
| Basaltic hornblende | 1.708 | 1.695 | 1.677 | 0.031 |
| Basaltic hornblende | 1.752 | 1.725 | 1.680 | 0.072 |

The inclined dispersion is distinct, with $\rho < v$, except in pargasite where one finds $\rho > v$.

Colorless, gray, green, greenish blue, brown, or black. The pleochroism is always distinct except in varieties (*edenite*) which are nearly or quite colorless. It is generally more intense in brown hornblende than in green. The pleochroic tints are numerous, but they all fall in the green, brown, and yellow categories. The absorption formula is Z > Y > X in all varieties.

---

[1] Hornblende with abundant iron. *Bull. Soc. Fr. Min.* 1903. XXVI. p. 126.

| | X | Y | Z |
|---|---|---|---|
| Common hornblende | pale green | pale brown | clear brown |
| Common hornblende | bluish green | clear green | clear yellow |
| Common hornblende | dark olive green | dark brownish green | clear brownish yellow |
| Common hornblende | dark brownish green | dark brown | clear yellow |
| Common hornblende | reddish yellow | brownish yellow | almost colorless yellow |
| Sorétite | dark green or greenish brown | green or brown | pale greenish yellow |
| Basaltic hornblende | dark brown | dark brown | pale brown or yellow |
| Basaltic hornblende | dark green | brownish green | greenish yellow |
| Basaltic hornblende | reddish brown | clear brown | pale yellow |
| Barkevikite | brown | reddish brown | brownish yellow |
| Barkevikite | various shades of green | clear green | greenish yellow |

Incl. Hornblende has many inclusions, but none that are characteristic. Vitreous inclusions occur in hornblende of the volcanic rocks; rutile is common in hornblende of the metamorphic rocks; ferruginous inclusions are not rare.

Alter. By ordinary alteration hornblende passes into chlorite, sometimes accompanied by epidote, calcite, siderite, quartz, etc. Less commonly hornblende alters to biotite, or to biotite and epidote. Still more rarely the alteration product is titanite. By the action of heat, and through refusion, hornblende is transformed into augite, often accompanied by magnetite, and occasionally by microlitic feldspars.

Occur. Hornblende occurs in igneous rocks, in contact rocks, and in ordinary metamorphic rocks. It is especially abundant in many basic igneous rocks, and in hornblende schists.

Lacroix (*Nouv. Arch. Mus.* IX. 1907. p. 89) has recently described a variety of hornblende in the rocks of Vesuvius with some unusual characters. It has an extinction angle ($Z \wedge c$) in 010 of $+33°$. The optic angle ($2V$) about the positive bisectrix is very large; the pleochroic colors are Z yellowish green, Y brownish yellow, X pale yellow, with $Y > \text{or} = Z > X$. The birefringence is only 0.014. Chemically the variety is characterized by high ferric iron (and titanic acid), and low alumina: it is also rich in magnesia and soda.

Diag. Hornblende is characterized by high relief, rather high (or very high) interference colors, cleavages making an angle of 124°, small maximum extinction angle in the vertical zone (0° to 25°), and distinct green or brown color (except edenite) with strong pleochroism.

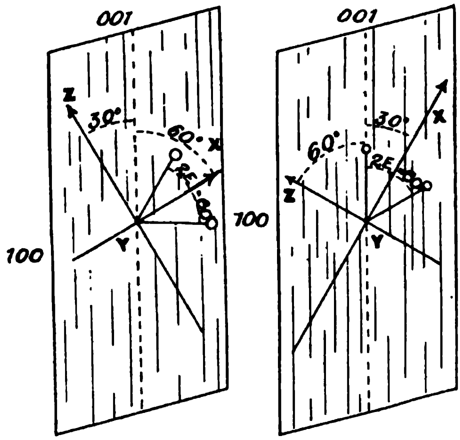
## KATOFORITE.

Monoclinic *Composition?*

Phys. Char. Similar to hornblende in physical characters, but distinguished from it by optical properties. Katoforite probably contains considerable soda, and perhaps also titanic acid.

Opt. Prop. The plane of the optic axes is parallel to 010, in which the axis Z makes an angle, varying from 30° to 60°, with the vertical crystallographic axis in the obtuse angle $\beta$.

$$(-)\ 2E = 60°$$



· Figs. 12 and 13.
Variable optical orientation of katoforite.

The absorption is quite characteristic with $Y > Z > X$. The pleochroic colors are also somewhat characteristic, as follows:—

Z = yellow, slightly greenish
Y = violet or violet red
X = brownish yellow

Occur. Katoforite is found in acid alkaline igneous rocks. Rare.

Diag. It is characterized by cleavages making an angle of 124°, a maximum extinction angle in the vertical zone exceeding 30° and less than 60°, and maximum absorption parallel to Y (that is, perpendicular to the elongation).

## ARFVEDSONITE.

Monoclinic $a:b:c::0.5496:1:0.2975$ $(Na_2,Ca,Fe)_4Si_4O_{12}$ with
$\beta = 75°\ 44'$ $(Ca,Mg)_2(Al,Fe)_4Si_2O_{12}$

Phys. Char. Crystals long prismatic, sometimes bladed. Similar to hornblende in physical characters, but contains considerable soda and iron. G. = 3.45. H. = 6. Fusible at 2 with intumescence. Insoluble.

Opt. Prop. The plane of the optic axes is parallel to 010 as in hornblende, but the axis X is more nearly parallel to the vertical crystallographic axis than the axis Z. Therefore the elongation is negative. The maximum extinction angle in the vertical zone is 14°. The optic angle is very large.

$$(-)\ 2V = \text{very large}$$

$$n_g = 1.708 \quad n_m = 1.707 \quad n_p = 1.687$$

$$n_g - n_p = 0.021$$

Color blue to black. The absorption is always $X > Y > Z$, and the pleochroism is intense in blue and green tints, as follows:—

Z = pale greenish yellow
Y = lavender blue
X = deep greenish blue

Alter. Arfvedsonite alters to brown acmite or green ægyrine with lepidomelane, often with separation of iron oxides and carbonate.

Occur. Arfvedsonite occurs in igneous rocks rich in soda, such as nepheline syenites.

Diag. It is characterized by negative elongation, peculiar pleochroism and absorption, and maximum extinction angle (14°) in the vertical zone; chemically, it is richer in sodium than hornblende.

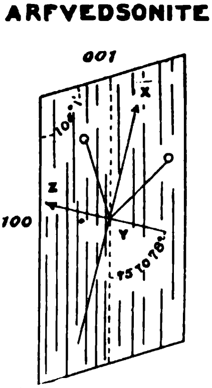


Fig. 14.
Optical orientation of arfvedsonite.

## RIEBECKITE.

Monoclinic $a:b:c::0.5475:1:0.2295$ $2NaFeSi_2O_6.FeSiO_3$

$$\beta = 76°\ 10'$$

Phys. Char. Crystals prismatic, vertically striated; rarely fibrous. Similar to hornblende in physical characters, but contains much soda and iron. H. = 4. G. = 3.44.

Opt. Prop. The plane of the optic axes is parallel to 010, in which the axis X makes an angle of 5° with the vertical crystallographic axis in the acute angle $\beta$. Therefore the elongation is negative. The optic angle is very large and the optic sign is positive. The birefringence is not strong; the intense color and pleochroism together with the strong dispersion prevent precise measures of the refringence and optic angle.

$$(+)\ 2V = \text{very large}$$

$$n_g > 1.687 \quad n_p < 1.687$$

$$n_g - n_p = 0.005$$

Color dark blue to black. The absorption is $X > Y > Z$. and the pleochroic colors are:—

Z = yellowish green
Y = blue
X = dark indigo blue, nearly black

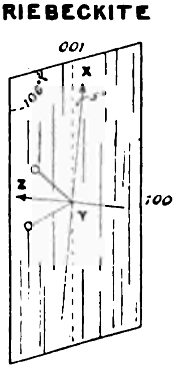


Fig. 15.
Optical orientation of riebeckite.

Occur. Riebeckite occurs in sodic igneous rocks, and in some metamorphic rocks.

Diag. It is characterized by intense pleochroism, intense color, strong dispersion, and negative elongation. The strong dispersion and deep color make it difficult to determine the sign of the elongation, which is important to distinguish the mineral from glaucophane.

## CROCIDOLITE.

MONOCLINIC $NaFeSi_2O_6.FeSiO_3$

PHYS. CHAR. Similar to riebeckite in physical characters; rich in soda and iron. Usually fibrous, sometimes more or less compactly interlaced. G. = 3.2-3.3. H. = 4. Fusible easily with intumescence. Insoluble.

OPT. PROP. The plane of the optic axes is parallel to 010, in which the axis X makes an angle of 18° to 21° with the vertical crystallographic axis in the acute angle $\beta$. The optic angle is large, and the sign is positive.

$$(+)\ 2E = 95° \text{ about}$$

$$n_z - n_p = 0.025$$

Color dark blue. The pleochroism is very distinct and somewhat variable:—

Z = nearly colorless yellow

Y = violet blue

X = greenish blue to sea green

OCCUR. Crocidolite seems to be always of secondary origin. It is found both in igneous and metamorphic rocks.

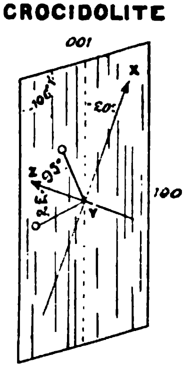


Fig. 16.
Optical orientation of crocidolite.

DIAG. It is characterized by negative elongation, large optic angle, pleochroism, and maximum extinction angle in the vertical zone.

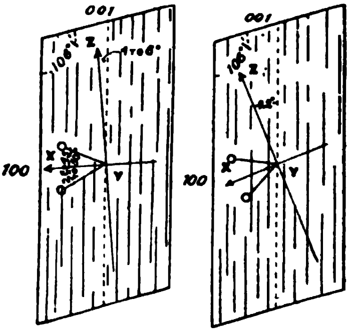
## GLAUCOPHANE.

MONOCLINIC $a:b:c::0.53:1:0.29$ $NaAlSi_2O_6.(Fe,Mg)SiO_3$

$\beta = 75°\pm$

PHYS. CHAR. Similar to hornblende in physical characters; rich in soda and iron. G. = 3.-3.14. H. = 6.-6.5. Readily fusible. Insoluble.

OPT. PROP. The plane of the optic axes is parallel to 010, in which the axis Z makes an angle of 4° to 6° with the vertical crystallographic axis in the obtuse angle $\beta$. The birefringence is somewhat variable. The optic sign is negative. Dispersion $\rho > v$ strong.



Figs. 16a and 16b.
Optical orientation of normal glaucophane (16a) and of glaucophane grading toward hornblende (16b).

$$(-)\ 2E = 44° \text{ to } 50°$$
$$n_g = 1.6390$$
$$n_m = 1.6381$$
$$n_p = 1.6212$$
$$n_g - n_p = 0.018 \text{ to } 0.022$$

Color lavender blue to bluish black. The pleochroism of glaucophane is very distinct and characteristic, but at the same time it is quite variable in intensity, and sometimes in tint parallel to Z. The intensity of the pleochroism seems to vary directly with the content of iron. The colors are:

Z = lavender blue to dark Prussian blue
Y = violet blue violet blue
X = colorless or yellowish to clear greenish yellow

Alter. Glaucophane seems to alter readily to a green sodic hornblende; often the transformation seems to be incomplete, and then the mineral, which may be considered an abnormal glaucophane, has a maximum extinction angle in the vertical zone of 16°, or even 20° or 22°. Furthermore, the color parallel to Z changes to a pale greenish blue.

Occur. Glaucophane occurs in schistose and in altered igneous rocks.

**Crossite** is intermediate between glaucophane and riebeckite in composition. G. = 3.16. The optic plane and obtuse bisectrix Z seem to be normal to 010 with $Y \wedge c = 16°$ to 30° in the acute angle $\beta$. The optic angle is variable to zero, and the dispersion is very strong. Birefringence, $n_g - n_p = 0.021$ at most. Pleochroism intense with Z dark violet, Y dark blue, X bright yellow. Murgoci suggests that there is a continuous series from glaucophane to crossite, the optic angle passing through zero, the variation corresponding to variation in the amount of $Fe_2(SiO_3)_3$ present.

Diag. Glaucophane is easily distinguished by its blue color, marked pleochroism, and positive elongation.

### ÆNIGMATITE (Cossyrite).

Triclinic $a:b:c::0.6778:1:0.3506$ $Na_4Fe_9(Al,Fe)_2(Si,Ti)_{12}O_{38}$
$\alpha = 90° \pm$ $\beta = 72°\ 49'$ $\gamma = 90° \pm$

Phys. Char. Crystals of ænigmatite much resemble those of the monoclinic amphiboles; the chief difference is in the angle $110 \wedge 1\bar{1}0$, (the cleavage angle) which is 114° 9′ instead of about 124° as in the other amphiboles. Crystals usually elongated || *c*. Twinning on 010 is common

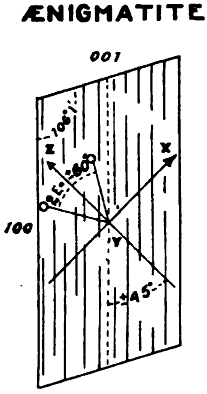


Fig. 17.
Optical orientation of ænigmatite.

and sometimes polysynthetic. The cleavages || 110 and 1$\bar{1}$0 are not as perfect as in other amphiboles. G. = 3.74-3.85. H. = 5.5 Readily fusible. Partly decomposed by acids.

Opt. Prop. The plane of the optic axes is nearly parallel to 010; the axis Z makes an angle of about 45° with the vertical crystallographic axis in 010 and about 4° in 100. The acute bisectrix is positive. The refringence is about like that of hornblende.

$$(+)\ 2E = 60° \text{ about}$$
$$n_g - n_p = 0.0064$$

Color black; streak reddish brown. The absorption is $Z > Y > X$, and the pleochroism is extremely intense as follows:—

Z = very dark brown
Y = dark chestnut brown
X = clear reddish brown.

Occur. Found in nepheline syenite and similar rocks. Rare.

**Rhönite** $[(Mg,Ca,Fe)_3(Al,Fe)_2(Si,Ti)_2O_{10}]$ is isomorphous with ænigmatite, and resembles it optically. Crystal habit like hornblende; twinning on 010. G. > 3.56; about 3.58. Transparent to opaque. Streak red brown. Optic plane inclined somewhat to 010 crossing the vertical axis from the right below to the left above. Extinction angle in sections normal to *c* 7°, measured on 010. Extinction angle (Z) in 010 in the acute angle $\beta$ 39°-40° from *c*. Refringence and birefringence about the same as in hornblende. Pleochroism strong in thin section with X brown, sometimes greenish, Y brown, Z dark red brown to black. Found in basic igneous rocks, especially basalts.

Diag. Distinguished by intense color, high refringence, absence of parallel extinction even in sections parallel to 100, and cleavage angle.

**ANALCITE,** see zeolite group.

## ANAPAITE.

Triclinic $a:b:c::0.875:1:0.597$. $FeCa_2(PO_4)_2+4H_2O$

$$\beta = 106°\ 47'$$

Phys. Char. Crystals often radiated, elongated || *c*. H. = 3.-4. G. = 2.81. Slowly soluble in acids.

Opt. Prop. The optic plane in 100 makes an angle of 15° with *c*. $n = 1.5753$. $2E = 127°$ Na. Color green.

Occur. Found in iron mines. Very rare.

## ANDALUSITE (Chiastolite).

Orthorhombic $a:b:c::0.986:1:0.702$ $Al_2SiO_5$

Phys. Char. Crystals always more or less elongated, parallel to the vertical axis; also columnar radiated, granular, massive. Cleavage good, parallel to 110, forming an angle of 90° 48′; in traces parallel to 100 and 010. G. = 3.1-3.2. H. = 7. Hardness and specific gravity often diminished by micaceous alteration. Infusible. Insoluble. Gives blue color with cobalt solution.

Opt. Prop. The optic plane is parallel to 010, with the negative acute bisectrix X perpendicular to 001.

$$(-)\ 2V = 83^\circ \text{ to } 85^\circ$$

$$n_g = 1.643 \quad n_m = 1.638 \quad n_p = 1.632$$

$$n_g - n_p = 0.011$$

**ANDALUSITE**

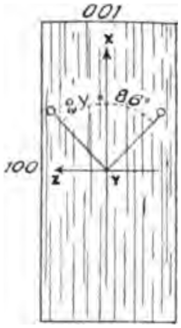


Fig. 18.
Optical orientation of andalusite.

Color rose red, violet, whitish; through alterations or inclusions may be gray, brown, green or black. Pleochroism variable in intensity even in a single crystal, with absorption X > Y > Z.

Z = colorless or very pale yellow
Y = colorless or very pale yellow
X = rose red

Incl. Andalusite in the metamorphic rocks often contains carbonaceous inclusions and is then known as *chiastolite*. These inclusions are nearly always distributed through the crystal in some geometrical form conforming to the symmetry of the mineral. Andalusite of the igneous rocks (pegmatite, etc.) has few inclusions, and none that are characteristic.

Alter. Andalusite alters readily to colorless mica (damourite); also, rarely, to a mixture of corundum and spinel, with rutile and feldspar.

Occur. Andalusite is found in granitic eruptive rocks and in metamorphosed sedimentary rocks.

Diag. It is distinguished by its rectangular form, very fine prismatic cleavage nearly at right angles, negative elongation and bisectrix, rose red pleochroism, weak birefringence and frequent carbonaceous inclusions. It is not attacked even by hydrofluoric acid.

**ANDESINE,** see feldspar group. **ANDRADITE,** see garnet group. **ANGLESITE,** see barite group. **ANHYDRITE,** see barite group. **ANNABERGITE,** see vivianite. **ANORTHITE,** see feldspar group. **ANORTHOCLASE,** see feldspar group. **ANTHOPHYLLITE,** see amphibole group. **ANTIGORITE,** see serpentine group.

### Apatite Group.

The minerals of the apatite group are phosphates, arsenates or vanadates of calcium or lead with chlorine or fluorine. Apatite is the only member of the group occurring commonly in rocks. Its hardness is greater and its density much less than those of others of the group. The minerals are all hexagonal with closely similar form, commonly in short prisms with basal or pyramidal terminations. Optically they are all negative and normally uniaxial, but the presence of arsenic seems to result in distinct biaxial character, suggesting imperfect hexagonal symmetry in the arsenate.

The minerals of the group are the following:—

| | | |
|---|---|---|
| Apatite | $c = 0.7346$ | $Ca_4(CaF)(PO_4)_3$<br>or $Ca_4(CaCl)(PO_4)_3$ |
| Pyromorphite | $c = 0.7362$ | $Pb_4(PbCl)(PO_4)_3$ |
| Mimetite | $c = 0.7224$ | $Pb_4(PbCl)(AsO_4)_3$ |
| Vanadinite | $c = 0.7122$ | $Pb_4(PbCl)(VO_4)_3$ |

### APATITE.

HEXAGONAL $c = 0.7346$ $Ca_4(CaF)(PO_4)_3$ or $Ca_4(CaCl)(PO_4)_3$

PHYS. CHAR. Crystals long, prismatic, or short tabular prisms sometimes highly modified. Prisms terminated by the base or by a pyramid. Also less commonly globular, reniform, or massive; fibrous, columnar or granular. Cleavage in traces || 0001. H. = 5. G. = 3.16-3.22. Fuses at about 5, giving reddish flame color. Soluble in HCl or $HNO_3$.

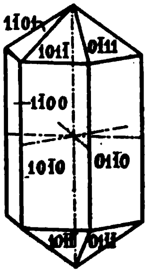


**Fig. 18a.**
A simple crystal form of apatite.

OPT. PROP. Optically negative. Usually strictly uniaxial, but occasionally the optic axial angle* ($2E$) exceeds 10°. This condition is found in apatite of the rock mass as well as in large crystals formed in cavities. Mallard, from the study of these anomalies, considers the mineral probably orthorhombic. The refringence is moderate; the birefringence quite weak. The indices of refraction, and birefringence, seem to vary with the content of fluorine or chlorine.

| | *Fluorapatite* | *Chlorapatite* |
|---|---|---|
| $n_g =$ | 1.6335 - 1.6388 | 1.6391 - 1.648 |
| $n_p =$ | 1.6316 - 1.6346 | 1.6341 - 1.643 |
| $n_g - n_p =$ | 0.0019 - 0.0042 | 0.0034 - 0.005 |

Color green, blue, red, white, gray, brown. Usually colorless in thin section; sometimes gray, blue, or brown, with the color irregularly distributed in clouds or lines, perhaps due to submicroscopic inclusions. Colored varieties weakly pleochroic with X > Z.

INCL. Occasionally apatite contains numerous dark inclusions; sometimes these are arranged in vertical lines or centrally, or zonally. They are sometimes fluid or gaseous. Such inclusions may give color to the mineral.

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* A. N. Winchell, *Amer. Geol.* XXVI. pp. 289, 301.

Alter. Apatite is quite fresh, even when the enclosing minerals have undergone complete alteration.

Occur. Apatite is very widely, but usually very sparsely, distributed in all kinds of rocks. It occurs most abundantly in regions of crystalline schists, as in Renfrew County, Ontario, and in the Odenwald. In Canada it is associated with metamorphosed limestone and accompanied by titanite, amphibole, zircon, pyroxene, garnet, vesuvianite. It is found in sedimentary rocks chiefly as the result of organic deposits. In igneous rocks it is somewhat more abundant in basic types; very rarely is it more than an accessory constituent. Finally, it is found in dikes and veins, sometimes in large crystals.

Diag. Apatite in its common crystal form is readily distinguished from other minerals by that means, and by its moderately high relief, very weak birefringence, and absence of distinct cleavage. Apatite differs from quartz in having higher relief, weaker birefringence and negative sign. Anhedral apatite is more easily confused with other minerals; it is distinguished from eudialyte by somewhat higher refraction, absence of distinct cleavage, and chemical reactions; melilite is optically of variable sign, has a distinct cleavage, and abnormal interference colors; gehlenite has somewhat higher relief than apatite; vesuvianite has still higher relief.

## PYROMORPHITE.

Hexagonal $c = 0.7362$ $Pb_4(PbCl)(PO_4)_3$

Phys. Char. Crystals prismatic, horizontally striated on prism faces. Also globular, reniform; fibrous or granular. Cleavage only in traces $\parallel$ $10\bar{1}0$ and $10\bar{1}1$. H. = 3.5-4. G. = 6.5-7.1, varying with the amount of arsenic replacing phosphorus; when calcium is present replacing lead the density falls to 5.9-6.5. B.B. fuses at 1.5 coloring the flame bluish green. Soluble in $HNO_3$.

Opt. Prop. Optically negative. Normally uniaxial, but biaxial whenever arsenic is present; the optic axial angle increases with increase of arsenic. The refringence is extremely high, but the birefringence is weak.

$$n_g = 2.0504\text{Na} \quad n_p = 2.0420\text{Na}$$
$$n_g - n_p = 0.0084\text{Na}$$

Color green, yellow, brown, gray, white. Pleochroic in crystals with Z green, X greenish yellow.

Alter. Alters uncommonly to galena, cerussite, calcite, etc.

OCCUR. Pyromorphite is found chiefly in veins with other lead ores; also, sparingly, disseminated in limestone in regions of lead ores.

**Mimetite** is the related arsenate of lead of similar form and habit, and yellow, brown or white color. G. $= 7.0$-$7.25$. It is distinguished from pyromorphite optically by the common biaxial character, the angle of the optic axes ($2E$) attaining 64°. In a basal section there are six triangular sectors with the axial plane in each parallel with the side of the hexagon and the negative acute bisectrix normal to 0001. The refringence is like that of pyromorphite, but the birefringence is stronger; $n_g = 2.1349$Na; $n_p = 2.1180$Na; $n_g - n_p = 0.0169$Na. Mimetite is found in lead veins or disseminations.

**Vanadinite** is the related vanadate of lead; it crystallizes in forms like those of pyromorphite, of deep red to pale yellow color. H. $=$ 2.75-3. G. $= 6.66$-$7.23$. Decomposed by HCl. Optically it is distinguished from the other minerals of the group by its strong birefringence; the relief is extremely high; $n_g = 2.354$Na; $n_p = 2.299$Na; $n_g - n_p = 0.055$Na. Vanadinite is abundant in the lead mining regions of Arizona and New Mexico; in other regions generally rare.

DIAG. Pyromorphite is distinguished from apatite by its much higher relief, and its mode of occurrence. It differs from mimetite in being uniaxial, or of small optic angle, and from vanadinite by much lower birefringence.

## APHTHITALITE.

RHOMBOHEDRAL $c = 1.284$ $(K,Na)_2SO_4$

PHYS. CHAR. Crystals rhombohedral, thin tabular || 0001; in groups, massive, encrusting, mammillary. Cleavage good || $10\bar{1}0$, in traces || 0001. H. $= 3.$-$3.5$. G. $= 2.63$-$2.66$. Fusible. Soluble in $H_2O$. Taste bitter, salty.

OPT. PROP. Uniaxial and positive. Refringence low. Color white, bluish, greenish.

$$n_g = 1.4993\text{Na} \quad n_p = 1.4907$$
$$n_g - n_p = 0.0086$$

OCCUR. Found about volcanoes, and in some salt deposits.

## APOPHYLLITE.

TETRAGONAL $c = 1.2515$ $H_7KCa_4(SiO_3)_8+4\frac{1}{2}H_2O$

PHYS. CHAR. Commonly in square prisms with basal planes, either flattened || 001, equidimensional, or more or less elongated || $c$. Base sometimes replaced by 111. Twinning plane 111 rare. Sometimes lamellar, massive; rarely in radiated prisms. Cleavage perfect || 001; imperfect || 110. H. $= 4.5$-$5$. G. $= 2.3$-$2.4$. Exfoliates, gives violet flame color, and fuses easily to white vescicular enamel. Decomposed by HCl with separation of slimy silica.

OPT. PROP. Apophyllite has low refringence and very weak birefringence; it is commonly uniaxial and positive, but in some cases it is negative, and "optic anomalies" are frequent. Thus a basal section often shows areas which are biaxial in addition to those uniaxial; furthermore, the interference figure may consist of black and white rings, instead of colored rings, or a single color may be wanting in the rings. In the biaxial areas the optic angle may vary from 0° to 50° or 60°, and the position of the optic plane may vary in a single crystal. In white light its trace may be parallel to 110 in a basal section or normal to 110; again, the optic plane for blue light may be at right angles to its position in red light. These anomalies may be produced by lateral pressure or by changes of temperature; they may be the result of molecular strains. Apophyllite may be strictly uniaxial at 260°C., at which temperature all the water is driven off.

$n_g = 1.5368$Na  1.5343Li

$n_p = 1.5347$Na  1.5328Li

$n_g - n_p = 0.0021$Na  0.0015Li

Colorless, white, grayish, yellowish, pink. Colorless in section.

Alter. Apophyllite is often cloudy on account of alteration; this is due sometimes to calcite, sometimes to a hydrous aluminum silicate; suggesting kaolinite. It also alters to pectolite.

Occur. Apophyllite occurs in cavities in basaltic igneous rocks, or, less commonly, in granite, gneiss, or similar rocks. It is associated very often with zeolites, or with datolite, pectolite, calcite.

Diag. Apophyllite has a higher refringence than that common in the zeolites; it differs from the uniaxial zeolites in having perfect basal cleavage. The tetragonal form and the peculiar optic anomalies are also quite characteristic.

**Aragonite Group.**

This is a group of carbonates of alkaline earth metals and lead, crystallizing in the orthorhombic system. The crystals very often twin on 110 so as to form pseudohexagonal prisms and pyramids. Acicular or columnar forms are common; globular or fibrous conditions less common. The minerals of the group all have cleavage parallel to 010 and 110 of varying perfection; and hardness of 3 to 4.

The minerals of the group are closely alike in optical properties. The acute negative bisectrix is parallel to *c* in all of them, and the optic angle is small. The relief is high, and even extremely high in cerussite. The birefringence is very strong, reaching an extreme in cerussite. The dispersion is weak except in cerussite.

The important minerals of the group are as follows:—

| | | |
|---|---|---|
| Aragonite | $a:b:c::0.623:1:0.721$ | $CaCO_3$ |
| Witherite | $a:b:c::0.603:1:0.730$ | $BaCO_3$ |
| Strontianite | $a:b:c::0.609:1:0.724$ | $SrCO_3$ |
| Cerussite | $a:b:c::0.610:1:0.723$ | $PbCO_3$ |

## ARAGONITE.

ORTHORHOMBIC $a:b:c::0.623:1:0.721$ $CaCO_3$

PHYS. CHAR. Crystals often acicular. Cleavage distinct parallel to 010, in traces parallel to 011 and 110; cleavages usually not noticeable in thin section because the mineral is in fibrous or acicular aggregates in rocks. Twinning [with 110 as the twinning plane, of the cyclic type producing pseudohexagonal forms] uncommon in thin sections. G. = 2.94. H. = 3.5-4. Infusible, but falls to a white powder. Soluble with effervescence.

OPT. PROP. The plane of the optic axes is parallel to 100; the acute bisectrix X is normal to 001. The refringence is high, and the birefringence very strong, producing iridescent colors, due to slight variations in thickness, similar to those of calcite. The dispersion is weak, $\rho < v$. The elongation is negative.

$$(-)\ 2E = 30°\ 54'\ \ (2V = 17°\ 50')$$

$$n_g = 1.686 \quad n_m = 1.682 \quad n_p = 1.530$$

$$n_g - n_p = 0.156$$

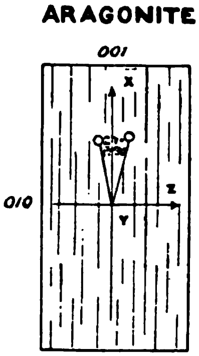

Fig. 19.
Optical orientation of aragonite.

Colorless, white, or stained. Colorless in section.

OCCUR. Aragonite occurs in many igneous and metamorphic rocks as an alteration product, probably usually due to the action of hot solutions.

*Ktypeite* is a name given by Lacroix to pisolites formerly considered aragonite, but shown to have G. = 2.58-2.70, $n_g - n_p = 0.020$, and positive sign. It is in part uniaxial, and in part biaxial with $2E = 50° \pm$. Changes to calcite upon heating.

*Bromlite* contains some barium, $(Ca,Ba)CO_3$. It resembles witherite in form. G. = 3.7. Cleavage imperfect || 110. Optic orientation as in aragonite. Dispersion very weak. Optic angle small, $2E = 9°\ 50'$. $n_g = 1.670$, $n_m = 1.670 \pm$, $n_p = 1.525$; $n_g - n_p = 0.145$. Rare.

DIAG. Characterized by acicular form leading to usual absence of cleavage, and by biaxial character (cf. calcite), and by position of the optic plane (cf. witherite, strontianite and cerussite).

## WITHERITE.

ORTHORHOMBIC $a:b:c::0.603:1:0.730$ $BaCO_3$

PHYS. CHAR. Similar to aragonite, but G. = 4.29-4.35. Twinning nearly always present. Fusible at 2 with yellowish green flame color. Soluble in dilute HCl.

**Opt. Prop.** The plane of the optic axes is parallel to 010 and the negative acute bisectrix is perpendicular to 001. Strong birefringence. Dispersion very weak $\rho > v$.

$$(-)\ 2E = 26° \ 30'$$
$$n_g = 1.677 \quad n_m = 1.676 \quad n_p = 1.529$$
$$n_g - n_p = 0.148$$

Color, white, yellowish, grayish. Colorless in thin section.

**Occur.** Usually associated with ores in veins. Rare.

**Diag.** Differs from aragonite in the position of the optic plane. Gives reactions for carbonic acid and barium.

## STRONTIANITE.

Orthorhombic $a:b:c::0.609:1:0.724$ $SrCO_3$

**Phys. Char.** Similar to aragonite, but G. = 3.68-3.71. Twinning often complex, very common. Cleavage nearly perfect parallel to 110; in traces parallel to 010. Fuses with difficulty, but swells and sprouts and gives crimson flame color. Soluble in HCl.

**Opt. Prop.** The plane of the optic axes is parallel to 010 and the acute negative bisectrix is perpendicular to 001. Dispersion weak $\rho < v$.

$$(-)\ 2E = 11° \ 48' \ (2V = 7° \ 5')$$
$$n_g = 1.6685 \quad n_m = 1.6666 \quad n_p = 1.5199$$
$$n_g - n_p = 0.1486$$

Color pale green, apple green, white, gray, yellow. Colorless in thin section.

**Occur.** Found in veins, in geodes in limestone, etc. Uncommon.

**Diag.** Differs from aragonite in the position of the optic plane and in having good cleavage parallel to 110.

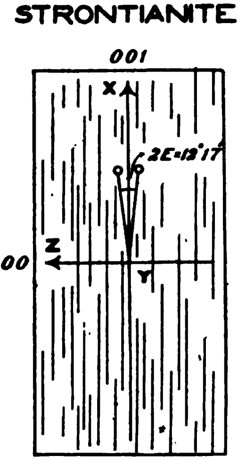

Fig. 20.
Optical orientation of strontianite.

## CERUSSITE.

Orthorhombic $a:b:c::0.610:1:0.723$ $PbCO_3$

**Phys. Char.** Similar to aragonite, but G. = 6.46-6.57. Cleavages || 110 and 021 distinct, || 010 and 012 in traces. Twins common; also granular massive. Fusible easily to metallic globule. Soluble in dilute $HNO_3$.

**Opt. Prop.** The plane of the optic axis is parallel to 010 and the acute negative bisectrix is perpendicular to 001. Marked dispersion with $\rho > v$. The axial angle decreases with decreasing temperature, becoming uniaxial at — 119° C.; then the axes open in a plane perpendicular to the former, and $2E$

reaches 11½° at — 190° C.

$$(-)\ 2E = 17^\circ\ 8'\ (2V = 8^\circ\ 14')$$

$$n_g = 2.078 \quad n_m = 2.076 \quad n_p = 1.804$$

$$n_g - n_p = 0.274$$

Color white, gray, grayish black. Colorless in thin section.

**Occur.** Found chiefly in veins associated with galena; also in limestone.

**Diag.** Differs from aragonite and witherite in small optic angle; from aragonite, witherite and strontianite in extremely high relief and extremely strong birefringence; from aragonite in the position of the optic plane.

CERUSSITE

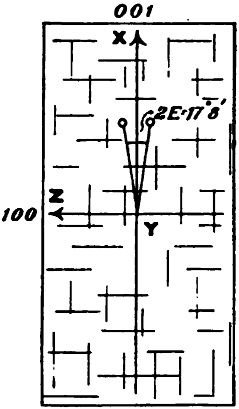

Fig. 21. Optical orientation of cerussite.

## ARDENNITE (Dewalquite).

**Orthorhombic** $a:b:c::0.4663:1:0.3135$ $H_{10}Mn_{10}Al_{10}Si_{10}V_2O_{55}$

**Phys. Char.** Crystals rare, prismatic, vertically striated. Cleavage easy || 010, distinct || 110. H. = 6.-7. G. = 3.62-3.66. Vanadium may be replaced in part by arsenic, which leads to the higher specific gravity. Easily fusible with intumescence. Nearly insoluble.

**Opt. Prop.** The plane of the optic axes is parallel to 100. The positive acute bisectrix is perpendicular to the easy cleavage 010. The elongation parallel to the vertical axis is negative. The refringence is high, and the birefringence rather strong. The angle of the optic axes is large; dispersion $\rho > v$ very strong.

$$(+)\ 2E = 73^\circ \text{ to } 74^\circ \text{ yellow}$$

$$n = 1.79 \pm$$

$$n. - n_p = 0.020$$

Color yellow to yellowish brown. In thin section the pleochroism is distinct in the following tints:—

| Sections 0.02 mm. | Sections 0.5 mm. |
|---|---|
| Z = very pale yellow | golden yellow. |
| Y = golden yellow | dark reddish brown |
| X = golden yellow | dark reddish brown |

**Occur.** Found in quartz veins with albite in schist. Very rare.

ARDENNITE

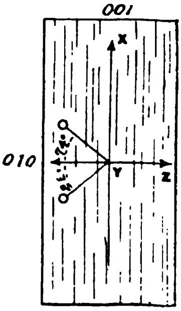

Fig. 22. Optical orientation of ardennite.

**Diag.** Distinguished from carpholite by the higher refringence and the negative elongation.

**ARFVEDSONITE,** see amphibole group. **ARGENTITE,** see galena.

## ARSENOLITE.

**Isometric** $As_2O_3$

Phys. Char. Crystals always octahedral, sometimes skeletal: also in fibrous or columnar crusts or botryoidal masses. H. = 1.5. G. = 3.71. Volatile in closed tube. Slightly soluble in hot water. Taste sweetish astringent.

Opt. Prop. Isotropic. Refringence high; $n = 1.755$ Na. Colorless, white, or stained yellowish or reddish by orpiment, sulphur, or realgar.

Occur. Found in metalliferous veins, about burning coal mines, and as a product of smelters.

**Senarmontite** ($Sb_2O_3$) is related chemically to arsenolite; its crystals are octahedral, but crystal and crystalline groups and masses are common. H. = 2.-2.5. G. = 5.22-5.3. Easily fusible and somewhat volatile. Soluble in HCl. Optically isotropic; frequently anisotropic, and similar to boracite or to the hexoctahedral type of garnet. The anisotropic character is explained by Mallard as due to twinning of a triclinic individual, by Bertrand, Gross-Bohle and Prendel as due to a monoclinic unit, and by Brauns as due to internal molecular strains. When anisotropic the mineral is biaxial with a large optic angle. Refringence very high; $n = 2.087$ Na. Colorless white, gray. Streak white. Alters to valentinite. Occurs chiefly as an oxidation product of stibnite in ore deposits.

**ARSENOPYRITE,** see marcasite.

## ASTROLITE.

**Orthorhombic?** Axial ratio unknown. $H(Na,K)_2(FeOH)FeAl(SiO_3)_5$

Phys. Char. In small globules radially fibrous or lamellar. Lamellar cleavage good. H. = 3.5. G. = 2.78. Fusible to gray enamel. Insoluble.

Opt. Prop. The negative acute bisectrix is normal to the lamellæ; the extinction is parallel with the elongation. The refringence is distinctly higher than that of Canada balsam. Dispersion weak $\rho > v$.

$$(-)\ 2E = 48° \pm$$

$$n_g - n_p = 0.021$$

Color greenish yellow. In thin sections siskin yellow parallel to elongation, pale yellow to colorless normal to elongation.

Occur. Found as inclusions in black quartz schists and in limestone fragments in diabase tuff. Very rare.

## ASTROPHYLLITE.

**Orth.** $a : b : c :: 0.9902 : 1 : 4.7101$ $(H,Na,K)_4(Fe,Mn)_4(Ti,Zr)Si_4O_{16}$

Phys. Char. Crystals often elongated || $c$, or flattened parallel to the cleavage 010. Cleavage very perfect || 010, in traces || 001. Cleavage laminæ brittle, not elastic like mica. G. = 3.3-3.4. H. = 3. Fusible easily after swelling. Decomposed by HCl, leaving scaly silica.

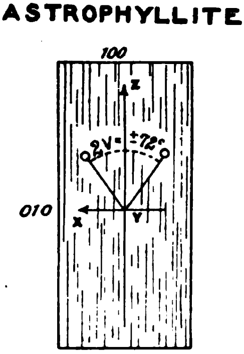

Fig. 23.

Optical orientation of astrophyllite.

Opt. Prop. The plane of the optic axes is parallel to 001; the positive acute bisectrix is perpendicular to 100. The sign of the elongation is variable. The angle of the optic axes has not been accurately measured.

$$(+)\ 2V = 70° \text{ to } 80°$$

$$n_g = 1.733 \quad n_m = 1.703 \quad n_p = 1.678$$

$$n_g - n_p = 0.055$$

Color bronze to gold yellow. Luster submetallic, pearly. The pleochroism is intense even in thin sections; the absorption formula of astrophyllite is $X > Y > Z$; the pleochroic colors are:—

| | *Astrophyllite.* | *Lamprophyllite.* |
|---|---|---|
| Z = | lemon yellow | gold yellow |
| Y = | orange yellow | straw yellow |
| X = | dark golden yellow | straw yellow |

Occur. Known only in nepheline syenite and in soda granite. Rare.

**Lamprophyllite** is similar in all known characters except the pleochroic formula (given above) and the absorption formula, $Z > Y = X$. It is found in syenite in Norway.

Diag. Differs from the micas in having brittle laminæ, the obtuse bisectrix perpendicular to the cleavage, and the maximum pleochroism transverse to the elongation of the laminæ.

## ATACAMITE.

Orthorhombic $a : b : c :: 0.661 : 1 : 0.753$ $Cu_2(OH)_3Cl$

Phys. Char. Crystals slender, prismatic, vertically striated; also tabular. Commonly in confused fibrous aggregates, stalactitic, in crusts, granular. Twinning on 110. Cleavage perfect || 010, in traces || 101. H. = 3.-3.5. G. = 3.76-4.31. Fusible, with azure blue flame having green border, to metallic copper. Easily soluble in acids.

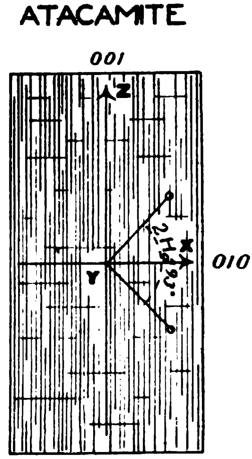

Fig. 24.
Optical orientation of atacamite.

Opt. Prop. The optic plane is parallel to 100; the negative acute bisectrix is normal to 010. Optic angle large, dispersion $\rho < v$ strong.

$$(-)\ 2V = 74° 56' \text{Tl}$$

$$n_g = 1.880, \ n_m = 1.861, \ n_p = 1.831$$

$$n_g - n_p = 0.049$$

Color bright green, emerald green, blackish green. Streak apple green. Luster adamantine to vitreous. Weakly pleochroic in thin section with Z grass green, Y yellowish green, X pale grass green.

Alter. Changes rather easily to malachite; also to chrysocolla.

Occur. Found in veins with other copper ores, especially malachite, cuprite. Also in sands, and formed about hot springs on brass or copper.

Diag. Differs from malachite in having parallel extinction, instead of extinction at about 23° in the vertical zone, and in having much weaker birefringence.

**AUGELITE**, see wavellite. **AUGITE**, see pyroxene group.

### AUTUNITE (Uranite).

Orthorhombic $a:b:c::0.9875:1:2.8517$ $Ca(UO_2)_2P_2O_8+8H_2O$

Phys. Char. Crystals thin tabular, of tetragonal aspect; also in foliated aggregates. Cleavage micaceous || 001, in traces || 010 and 100. Flattening || 001 resulting in apparent elongation which is of positive sign. Twinning plane || 110 with irregular intergrowths. G. $= 3.05$ to $3.19$. H. $= 2.-2.5$. Soluble in $HNO_3$.

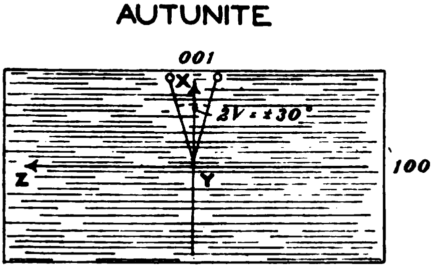

Fig. 25. Optical orientation of autunite.

Opt. Prop. The plane of the optic axes is parallel to 010; the negative acute bisectrix perpendicular to 001. Dispersion $\rho > v$.

$(-)$ $2E = 60°$ $(2V = 30° \pm)$

$n_g = 1.577$ $n_m = 1.575$ $n_p = 1.553$

$n_g - n_p = 0.024$

Color lemon to sulphur yellow. In thin section golden yellow without pleochroism.

Occur. Found in gneiss, hornstone, etc., and associated with tin and silver ores.

Diag. Characterized by golden yellow color without pleochroism, acute negative bisectrix perpendicular to micaceous cleavage, brittle laminæ.

### AXINITE.

Triclinic $a:b:c^*::0.6019:1:0.8267$ $H(Ca,Fe,Mn)_3Al_2BSi_4O_{16}$

$\alpha = 121°\ 32'$ $\beta = 44°\ 42'$ $\gamma = 140°\ 20'$

Phys. Char. Crystals usually wedge-shaped (whence the name), like a lens with flat surfaces; also massive; cleavage easy || 1$\bar{1}$2, 010 and 1$\bar{3}$0, in traces || 001. H. $= 6.5-7$. G. $= 3.29-3.30$. Fusible at 2 with intumescence and green flame color. Insoluble.

Opt. Prop. The negative acute bisectrix is very nearly perpendicular to 011. In this face the trace of the optic plane makes an

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[*] There is no agreement as to the fundamental form of axinite. The parameters given above are those of Des Cloizeaux. For their relation to other notations see Frazier: *Amer. Jour. Sci.* XXIV, 442, 1882.

angle of 40° with $1\bar{1}0$ and an angle of 24° 40′ with 001. Crossed dispersion very slight. Inclined and horizontal dispersion noticeable. The dispersion of the optic axes which is scarcely perceptible in oil is very marked in air with $\rho < v$. Angle of the optic axes somewhat variable, even in a single crystal.

$$(-)\ 2V = 71° \text{ to } 74°.$$

$$n_g = 1.681 \quad n_m = 1.678 \quad n_p = 1.672$$

$$n_g - n_p = 0.009$$

Color brown, gray, dull blue, yellow. Luster vitreous. The pleochroism is very distinct in thick sections, but often entirely lacking in thin sections.

| Sections 3. mm. | Sections 0.02 mm. |
|---|---|
| Z = clear olive yellow | colorless |
| Y = intense violet | pale violet to colorless |
| X = cinnamon brown | colorless |

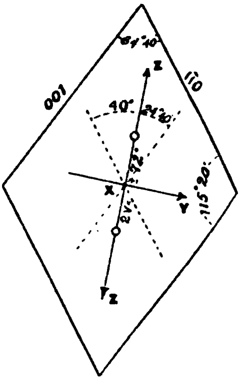


Fig. 26.
Optical orientation of axinite as seen in a section parallel to 011.

Occur. Usually the result of fumarolic action in metamorphosed rocks; also found in basic eruptives and in ore deposits.

Diag. The form is characteristic. Distinguished from orthoclase in thin section by much higher relief.

## AZURITE.

Monoclinic $a:b:c::0.8501:1:0.8805$ $Cu_3(OH)_2(CO_3)_2$

$$\beta = 87° \ 36'$$

Phys. Char. Crystals varied in habit, usually with many planes; tabular, prismatic, elongated || $c$ or || $b$, etc. Twinning plane $\bar{2}01$ or $\bar{1}01$ not common. Cleavage perfect || 021, imperfect || 100, in traces || 110. H. = 3.5-4. G. = 3.77-3.83. B.B. fuses at 2, coloring the flame green. Soluble in acids with effervescence.

Opt. Prop. The plane of the optic axes is parallel to 010; the positive acute bisectrix makes an angle of 12½° with the vertical axis in the acute angle $\beta$. The angle of the optic axes is large; axial dispersion considerable, with $\rho > v$; also distinct horizontal dispersion.

$$(+)\ 2E = 151° \ (2H = 82° \ 5')$$

$$n_g - n_p = 0.200$$

Color azure to berlin blue; in thin section very pale blue.

Alter. Azurite alters rather easily to malachite; also, rarely, to native copper.

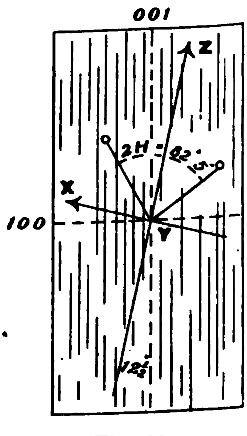


Fig. 27.
Optical orientation of azurite.

OCCUR. Usually formed in veins or cavities by percolating waters; commonly associated with malachite, cuprite, etc.

**BABINGTONITE,** see pyroxene group.

**BADDELEYITE.**

MONOCLINIC $a:b:c::0.9871:1:0.5114$ $ZrO_2$

$\beta = 81° 15'$

PHYS. CHAR. Crystals tabular || 100 commonly twinned on 100, sometimes in polysynthetic lamellæ; twinning on 110 of both contact and penetration types, also in laminæ; twinning on 201 rare. Cleavage perfect || 001, indistinct || 010; parting || 110. H. = 6.5. G. = 5.5-6.0. Nearly infusible and insoluble.

OPT. PROP. The plane of the optic axes is parallel to 010; the negative acute bisectrix makes an angle of about 12° with *c* in the obtuse angle $\beta$. The refringence is high and birefringence strong. The angle of the optic axes is rather large. Dispersion is inclined.

$$(-)\ 2E = 70° - 75°$$

Color variable, yellow, brown, black, colorless. In thin section colorless, yellow or brown, with the color often irregularly distributed. In thick section pleochroic with Z reddish brown, Y oil green, X reddish brown, and $X > Y > Z$.

OCCUR. Found in gem bearing sands of Ceylon; also in pyroxenite of Brazil, and in nepheline syenite of Sweden. Rare.

**Barite Group.**

This is a group of sulphates of alkaline-earth metals and lead, crystallizing in the orthorhombic system. The crystals are often tabular parallel to 001, or prismatic and elongated parallel to any crystal axis. Globular and fibrous conditions not uncommon. Cleavage in all the minerals of the group parallel to 001 and 110 except in anhydrite where it is parallel to 001, 010, and 110. The hardness ranges from 2.5 to 3.5.

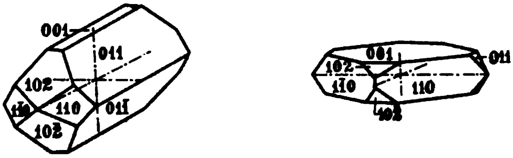
The optic plane is parallel to 010 in all the minerals of the group, and the positive acute bisectrix is normal to 100. The dispersion is $\rho < v$.

| | | |
|---|---|---|
| Barite | $a:b:c::0.815:1:1.314$ | $BaSO_4$ |
| Celestite | $a:b:c::0.779:1:1.280$ | $SrSO_4$ |
| Anglesite | $a:b:c::0.785:1:1.289$ | $PbSO_4$ |
| Anhydrite | $a:b:c::0.893:1:1.0008$ | $CaSO_4$ |

**BARITE.**

ORTHORHOMBIC $a:b:c::0.815:1:1.314$ $BaSO_4$

PHYS. CHAR. Crystals often tabular || 001. Cleavage perfect || 001 and also 110, imperfect || 010. Twinning on 100



Figs. 28 and 28a. Simple crystal forms of barite.

common. H. = 2.5-3.5. G. = 4.3-4.6. Fusible at 3 with yellowish green flame. Insoluble in acids.

Opt. Prop. The plane of the optic axes is parallel to 010; the positive acute bisectrix is perpendicular to 100. Colorless. Dispersion $\rho < v$.

$$(+)\ 2V = 35° \text{ to } 37°.$$

$$n_g = 1.647 \quad n_m = 1.637 \quad n_p = 1.636$$

$$n_g - n_p = 0.011$$

Color white; also yellowish, gray, blue, red, brown. Colorless in thin section.

Occur. Commonly found in connection with veins of metallic ores; also in limestones and sandstones, and in cavities of amygdaloids, etc.

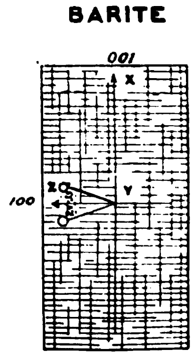


Fig. 28b. Optical orientation of barite.

Diag. Distinguished from celestite by higher relief and stronger birefringence. Anhydrite has three easy rectangular cleavages and very strong birefringence. Anglesite has very high relief and rather strong birefringence.

## CELESTITE.

**Orthorhombic** $a:b:c::0.779:1:1.280$ $SrSO_4$

Phys. Char. Resembles barite, but G. = 3.95-3.97. Fusible at 3 with crimson flame. Insoluble in acids.

Opt. Prop. The plane of the optic axes is parallel to 010 and the positive acute bisectrix is normal to 100. Dispersion $\rho < v$.

$$(+)\ 2V = 51°$$

$$n_g = 1.631 \quad n_m = 1.623 \quad n_p = 1.622$$

$$n_g - n_p = 0.009$$

Color, white, bluish, reddish. Colorless in thin section.

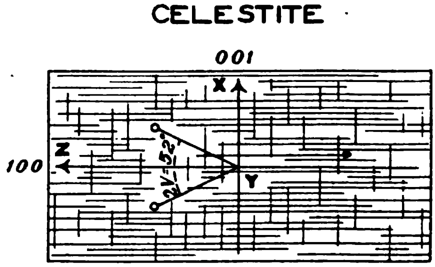


Fig. 29. Optical orientation of celestite.

Occur. Usually associated with limestone or sandstone; also found in metalliferous veins, and in beds of gypsum, rock salt, clay, etc.

**Diag.** Distinguished from barite by lower relief, weaker birefringence and large optic axial angle. Anhydrite has three rectangular easy cleavages and very strong birefringence. Anglesite has very high relief and rather strong birefringence.

## ANGLESITE.

**Orthorhombic** $a:b:c::0.785:1:1.289$ $PbSO_4$

**Phys. Char.** Resembles barite in physical characters, but G.= 6.12 to 6.39, and cleavages || 001 and 110 are interrupted, though distinct. Fusible with decrepitation at 1.5. Slowly soluble in $HNO_3$.

**Opt. Prop.** The plane of the optic axes is parallel to 010 and the positive acute bisectrix is normal to 100. Dispersion $\rho < v$.

$$(+)\ 2V = 66° \text{ to } 75°.$$

$$n_g = 1.897 \quad n_m = 1.883 \quad n_p = 1.877$$

$$n_g - n_p = 0.020$$

Color white, yellowish, grayish, greenish, bluish. Colorless in section.

**Occur.** Usually associated with galena; sometimes also with cerussite in veins and ore beds; usually formed by alteration of galena.

**Diag.** Characterized by very high relief, rather strong birefringence and large optic angle.

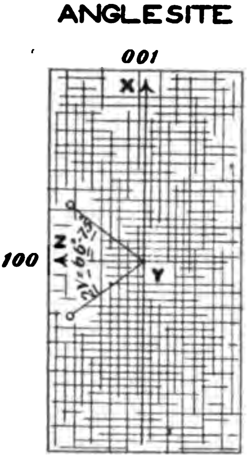


Fig. 30.
Optical orientation of anglesite.

## ANHYDRITE.

**Orthorhombic** $a:b:c::0.8932:1:1.0008$ $CaSO_4$

**Phys. Char.** Resembles barite in physical characters, but G. = 2.90 to 2.98, and cleavages || 001 very perfect, 010 perfect, 100 somewhat less perfect. Fusible at 3 with reddish yellow flame color. Soluble in HCl.

**Opt. Prop.** The plane of the optic axes is parallel to 010, and the positive acute bisectrix is normal to 100. Dispersion $\rho < v$.

$$(+)\ 2V = 42°\ 8'$$

$$n_g = 1.614 \quad n_m = 1.576 \quad n_p = 1.571$$

$$n_g - n_p = 0.043$$

Color white, grayish bluish, red. Colorless in thin section.

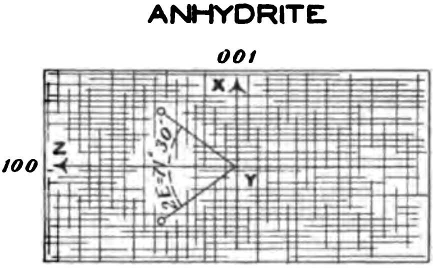


Fig. 31. Optical orientation of anhydrite.

**Alter.** Changes by hydration to gypsum, sometimes in large masses.

Occur. Usually associated with gypsum and rock salt.

Diag. The rectangular cleavages in three directions and the strong birefringence are characteristic.

## BARYLITE.

Orthorhombic $a:b:c::0.408:1:?$ $Ba_4Al_4Si_7O_{24}$

Phys. Char. Crystals prismatic, tabular. Cleavage || 100, 010, 110, and 001. Prismatic cleavage good. H. = 7. G. = 4. Infusible. Insoluble.

Opt. Prop. The optic plane is parallel to 001; the acute bisectrix Z is normal to 100. Refringence high. Dispersion $\rho > v$ weak. Color milk white.

$$(+)\ 2V = 86°$$
$$n_g = 1.69 \text{ approx.} \quad n_m = 1.685 \quad n_p = 1.68 \text{ approx.}$$
$$n_g - n_p = 0.014$$

Occur. Found in limestone in Sweden. Very rare.

## BARYTOCALCITE.

Monoclinic $a:b:c::0.772:1:0.625$ $BaCa(CO_3)_2$

$$\beta = 73° 52'$$

Phys. Char. Crystals pyramidal prismatic. Massive. Cleavage perfect || 110, imperfect || 001. H. = 4. G. = 3.65. Fusible difficultly with yellowish green flame color. Soluble in HCl.

Opt. Prop. The optic plane and obtuse bisectrix Z are normal to 010; $X \wedge c = +64\frac{1}{2}°$. Optic angle small. Very weak horizontal dispersion with $\rho > v$ weak.

$$(-)\ 2E = 23° 15' \text{ to } 24° 53'$$
$$n_g = 1.686 \quad n_m = 1.684 \quad n_p = 1.525$$
$$n_g - n_p = 0.161$$

Color white, grayish, greenish, yellowish. Streak white.

Occur. Found in limestone, with barite and fluorite. Very rare.

**BAUXITE,** see diaspore.

## BECKELITE.

Isometric $Ca_3(Ce,La,Di)4Si_3O_{15}$

Phys. Char. Crystals commonly octahedral; also dodecahedral and modified. Also granular. Cleavage distinct || 100. H. = 5. G. = 4.15. Infusible. Soluble in HCl.

Opt. Prop. Small crystals completely isotropic; large crystals sometimes anisotropic with weak birefringence. Refringence high. Color brown; in thin section light yellow.

Occur. Found in a pegmatite of albite, nephelite and magnetite. Rare.

Diag. Distinguished from pyrochlore by its ready solubility in HCl.

## BENITOITE.

HEXAGONAL $c = 0.733$ $BaTiSi_3O_9$

PHYS. CHAR. Crystals pyramidal or tabular. Cleavage imperfect || $10\bar{1}1$. H. = 6.-6.5. G. = 3.65. Fusible quietly at 3. to transparent glass. Soluble in HF.

OPT. PROP. Uniaxial and positive. Refringence high. Birefringence strong.

$$n_g = 1.80 \quad n_p = 1.77$$
$$n_g - n_p = 0.03$$

Color blue, purple, colorless, varying in a single crystal. Colored parts strongly pleochroic with Z purple, indigo, greenish blue to colorless, and X colorless.

OCCUR. Found in veins or geodes with natrolite in glaucophane schist, in serpentine. Very rare.

## BERTRANDITE.

ORTHORHOMBIC $a:b:c::0.569:1:0.597$ $H_2Be_4Si_2O_9$

PHYS. CHAR. Crystals are always flattened, sometimes || 001; they may be also elongated || $c$. Habit quite varied, sometimes distinctly hemimorphic. Twinning uncommon; twins commonly have a reëntrant angle of about 60°; twinning plane may be 011, 130 or 031. Cleavage or parting often well developed || 001, 110, 010, 100. H. = 6.-6.5. G. = 2.586-2.60. B.B. infusible, but becomes opaque white. Insoluble in acids.

OPT. PROP. The plane of the optic axes is parallel to 010; the negative acute bisectrix is normal to 100. The angle of the optic axes is large; axial dispersion weak with $\rho < v$. The relief is distinct, and the interference colors reach the upper second order.

$$(-)\ 2V = 75° \pm$$
$$n_g = 1.611 \quad n_m = 1.593 \quad n_p = 1.588$$
$$n_g - n_p = 0.023$$

Colorless, or stained by limonite. Luster vitreous; pearly on 001.

ALTERATION of bertrandite is unknown: circulating waters may introduce and stain it with limonite.

OCCUR. Unknown as a rock constituent; found only in pegmatite, or in veins. Often associated with quartz, orthoclase, albite, apatite, beryl, tourmaline, herderite.

DIAG. Distinguished from zeolites and muscovite by having parallel extinction and a cleavage 001 of negative sign; further, this cleavage is normal to a positive obtuse bisectrix. Finally, the forms and pearly luster on 001 are quite distinctive.

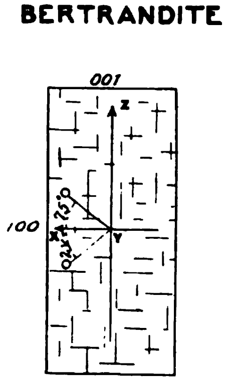


Fig. 32.
Optical orientation of bertrandite.

## BERYL.

HEXAGONAL $c = 0.499$ $Be_3Al_2(SiO_3)_6$

PHYS. CHAR. Usually in long prismatic crystals with indistinct basal (0001) cleavage. Also massive, coarse columnar or granular to compact. H. = 7.5-8. G. = 2.63-2.80. Nearly infusible. Insoluble in acids.

Opt. Prop. Uniaxial and negative, with negative elongation. Optic anomalies are common; according to Mallard the hexagonal symmetry is due to twinning of orthorhombic individuals as trillings. In thin section the only evidence of the pseudohexagonal character is the slight separation of the black cross, which is common. According to Lacroix basal sections showing anomalies are divided into six biaxial sectors, often with a uniaxial center.

The indices seem to vary in different crystals thus:

| | Beryl from Brazil | Colorless beryl from La Villeder | Pink beryl from Madagascar |
|---|---|---|---|
| $n_g$ = | 1.5724 | 1.5785 | 1.5825 ω |
| $n_p$ = | 1.5673 | 1.5735 | 1.5761 ε |
| $n_g - n_p$ = | 0.006 (average) | | |

Color green, blue, yellow, white, rose red. Luster vitreous, sometimes resinous. Colorless in thin sections; more or less pleochroic in thick sections with varying colors as follows:—

| | pink beryl | yellow beryl | blue beryl | emerald |
|---|---|---|---|---|
| Z = | colorless | golden yellow | greenish blue to colorless | yellowish green |
| X = | pale pink | reddish yellow | blue | sea green |

But in some cases the absorption formula is Z > X.

Alter. Beryl alters rather easily to produce kaolin in earthy masses. This transformation usually affects the fissures of the mineral, and renders it opaque and soft.

Occur. Beryl is found in pegmatite dikes, in veins associated with tin ores, and in micaschists.

Diag. Distinguished optically from apatite only by slightly lower relief and slightly stronger birefringence; also in thick sections by pleochroism. Beryl is harder than apatite and insoluble in acids. It also differs from apatite in its mode of occurrence, and alters much more easily.

## BERYLLONITE.

Orthorhombic $a:b:c::0.5724:1:0.5490$ $NaBePO_4$

Phys. Char. Crystals short prismatic to tabular; prism faces often vertically striated. Crystals often very complex. Twinning on 110 gives pseudohexagonal forms. Cleavage perfect || 001, imperfect || 100, indistinct || 110. H. = 5.5-6. G. = 2.845. Fusible at 3 to cloudy glass. Soluble.

Opt. Prop. The plane of the optic axes is parallel to 100; the negative acute bisectrix is normal to 001. The mineral has no relief. The birefringence is weak. The angle of the optic axes is large; dispersion weak with $\rho < v$.

$$(-)\ 2V = 67^\circ\ 34'\ (2E = 121^\circ).$$

$$n_g = 1.5608 \quad n_m = 1.5579 \quad n_p = 1.5520$$

$$n_g - n_p = 0.0088$$

Colorless, white, yellowish.

Incl. Cavities (with or without liquid inclusions) are often arranged parallel to the vertical axis.

Occur. Found in vein material in granite. Rare.

**BIOTITE,** see mica group. **BLOEDITE,** see löweite. **BOBIERRITE,** see vivianite. **BOLÉITE,** see percylite. **BOOTHITE,** see melanterite.

## BORACITE.

Orthorhombic (Pseudoisometric) $Mg_7Cl_2B_{16}O_{30}$

Phys. Char. Crystals cubic or dodecahedral, modified by tetrahedral forms. Both tetrahedrons may give an octahedral aspect. Also fine granular to earthy. Twinning plane 111 rare, in penetration forms. Cleavage in traces || 111. H. = 7. G. = 2.9-3. B.B. fuses at 2 with intumescence coloring the flame green. Soluble in HCl.

Opt. Prop. At ordinary temperatures boracite has a birefringence slightly higher than that of quartz. This disappears when the mineral is heated to 265°C.; it then becomes truly isometric and isotropic. The crystals of boracite are explained as due to various types of twinning of an orthorhombic individual in which the angle of the optic axes is very large. In one type a dodecahedron is made up of twelve individuals, in each of which the plane of the optic axes is parallel to the long diagonal of the rhombic crystal face to which the bisectrix is normal. The refringence is considerable. Color white or tinted.

$$(+)\ 2V = \text{nearly } 90^\circ$$
$$n_g = 1.6730 \quad n_m = 1.6670 \quad n_p = 1.6622$$
$$n_g - n_p = 0.0108$$

Alter. Boracite takes up water slowly, and becomes cloudy.

Occur. It is found in beds of gypsum, anhydrite and salt.

Diag. The optical characters combined with the form are quite distinctive.

## BORAX.

Monoclinic $a:b:c::1.0995:1:0.5632$ $Na_2B_4O_7+10\,H_2O$

$$\beta = 73^\circ\ 25'$$

Phys. Char. Crystals usually simple prismatic, sometimes large. Twinning plane 100. Cleavage perfect || 100, imperfect || 110. H. = 2.-2.25. G. = 1.69-1.72. B.B. enlarges and fuses to transparent glass. Soluble in $H_2O$.

Opt. Prop. The plane of the optic axes and the negative acute bisectrix are normal to 010; the obtuse bisectrix makes an angle with the vertical axis in the acute angle $\beta$ of 57° in red light and 55° in blue light. The refringence is very low and the birefringence is moderately strong. The angle of the optic axes is moderate, but the axial dispersion $\rho > v$ is marked, and crossed dispersion is also very distinct.

$$(-)\ 2V = 39°\ 25'$$

$$(2E = 59°\ 53'\ \text{Li},\ 2E = 58°\ 18'\ \text{Tl})$$

$$n_g = 1.4715 \quad n_m = 1.4686 \quad n_p = 1.4468$$

$$n_g - n_p = 0.0247$$

Color white, grayish, bluish, greenish. Colorless in section.

Occur. An abundant deposit from certain salt lakes, as in Thibet and California.

Diag. The very low refringence, moderately strong birefringence, and distinct dispersion, both axial and crossed, are characteristic, especially when combined with the peculiar mode of occurrence.

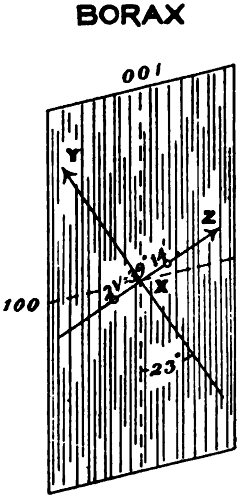


Fig. 33.
Optical orientation of borax.

## BORNITE (Erubescite).

Isometric $Cu_3FeS_3$

Comp. Exact chemical formula somewhat uncertain.

Phys. Char. Crystals commonly cubic or modified; twinning on 111 in penetration forms of hexagonal aspect. Commonly massive, granular. Cleavage only in traces || 111. H. = 3. G. = 4.9-5.4. Before the blowpipe fuses in reducing flame to a brittle magnetic globule. Soluble in $HNO_3$ with separation of sulphur.

Opt. Prop. Opaque. Color reddish brown, but only seen on fresh fracture, which soon tarnishes to red and blue. Luster metallic. In reflected light reddish brown, red and blue colors.

Occur. Common ore of copper, usually associated with chalcopyrite, chalcocite, etc. It occurs sometimes in pegmatitic veins; more commonly in ordinary mineral veins. It is also produced by the action of hot springs upon copper coins; and in metallurgical furnaces.

## BOTRYOGEN.

Monoclinic $a:b:c::0.652:1:0.599$ $Mg(FeOH)(SO_4)_2+7H_2O$

$$\beta = 62°\ 26'$$

Phys. Char. Crystals short, prismatic; usually botryoidal or reniform. Cleavage distinct || 110, in traces || 120. H. = 2.-2.5. G. = 2.-2.14. Intumesces and falls to reddish yellow powder. Partly soluble in hot $H_2O$.

Opt. Prop. The optic plane and the obtuse bisectrix X are normal to 010; $Z \wedge c = -12°$. Optic angle not large; dispersion $\rho > v$.

$$(+)\ 2V = 40°\ 54'$$

$$n_g = 1.572 \quad n_m = 1.548 \quad n_p = 1.544$$

$$n_g - n_p = 0.028$$

Color dark red. Streak yellow. In thin section pleochroic with Z orange, Y pink to colorless, X pale yellow to colorless.

Occur. Found in copper mines coating gypsum and pyrite. Also in veins with cinnabar, sulphur, epsomite, etc. Rare.

**BOUSSINGAULTITE,** see picromerite. **BOWLINGITE,** see serpentine group. **BRANDISITE,** see clintonite group.

**BRAVAISITE.**

Orth. Axial ratio unknown $H_8(K_2,Mg,Ca)_2(Al,Fe)_4Si_9O_{30}$

Phys. Char. In thin scales and lamellar or fibrous masses. Soapy feel. Looks like clay. Pasty when wet. When dry, H. = 1.-2. G. = 2.6. Easily fusible to a white globule. Incompletely soluble in acids.

Opt. Prop. The negative acute bisectrix is normal to the lamellæ; extinction parallel to elongation. Birefringence strong. $2E = 40° \pm$. Color greenish gray.

Occur. Found in thin layers in coal and bituminous schists. Rare.

**BREWSTERITE,** see zeolite group.

**BROCHANTITE.**

Orthorhombic $a:b:c::0.7739:1:0.4871$ $Cu_4(OH)_6SO_4$

Phys. Char. Crystals prismatic, somewhat elongated || *c*, vertically striated; sometimes elongated || *b*. Acicular groups; encrusting; massive. Cleavage perfect || 010. H. = 3.5-4. G. = 3.9. Fusible.

Opt. Prop. The plane of the optic axes is parallel to 100; the negative acute bisectrix is normal to 010. The angle of the optic axes is large. Color emerald green.

$$(-)\ 2H_a = 96° \pm$$

Occur. In veins with other copper minerals, as malachite, atacamite, chalcopyrite, etc.

**Langite** $[Cu_4(OH)_6SO_4 + H_2O]$ is chemically related to brochantite; it is orthorhombic with $a:b:c::0.535:1:0.635$. Crystals small, complex. Twinning on 110 like aragonite. Fibrous or lamellar crusts. Cleavage || 001 and 010. H.= 2.5-3. G.= 3.48-3.50. Heating changes the color through green to black. Optic plane parallel to 010; acute bisectrix X normal to 001. Color blue to greenish blue. Pleochroic. Found in slaty schists. Rare.

**Herrengrundite** $[(Cu,Ca)_5(OH)_6(SO_4)_2 + 3H_2O]$ is another related mineral; it is monoclinic with $a:b:c::1.816:1:2.800$ and $\beta = 88° 50'$. Crystals tabular || 001, six-sided, usually in spherical groups. Twinning on 001. Cleavage perfect || 001, distinct || 110, in traces || $\bar{1}02$. H. = 2.5. G. = 3.13. Fusible. Soluble in acids. Optic plane and obtuse bisectrix Z normal to 010; X nearly parallel to *c*. $2E = 65° 18'$ to $66° 53'$ Na. Dispersion $\rho < v$ strong. Color emerald green to bluish green.

Streak light green. Pleochroic, with Z yellowish green, Y bluish green X? Found in quartz conglomerate with malachite and calcite. Very rare.

**Serpierite** is a basic sulphate of copper and zinc in orthorhombic tabular tufted crystals with $a:b:c::0.859:1:1.364$. Optic plane || 100; acute bisectrix X normal to 001. $2E=66°-67°$ Li; dispersion $\rho > v$ strong. Color bluish green. Found on smithsonite at zinc mines of Greece. Very rare.

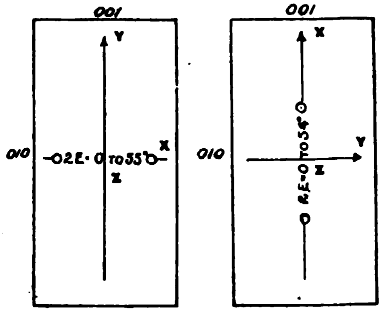
**BROMLITE**, see aragonite. **BRONZITE**, see pyroxene group.

## BROOKITE.

ORTHORHOMBIC $a:b:c::0.8416:1:0.4772$ $TiO_2$

PHYS. CHAR. Known only in crystals which are of variable habit. Cleavages in traces || 110 and 001. H. = 5.5-6. G. = 3.87-4.08. Infusible. Insoluble even in HF.

OPT. PROP. The acute positive bisectrix (Z) is always perpendicular to 100, but in many crystals the plane of the optic axes is parallel to 001 for red and yellow light with $\rho > v$ and parallel to 010 for blue and green light with $\rho < v$; the mineral is uniaxial for a certain yellowish green tint. In some crystals the plane of the optic axes is parallel to 001 for light of all colors. The axial angle decreases with decreasing temperature, so that it is uniaxial for yellow light at —190°C.



Figs. 34 and 35. Optical orientation of brookite for the red and blue ends of the spectrum respectively.

$$(+)\ 2E = 55° 2' \text{ Li}$$
$$2E = 30° 16' \text{ Na}$$
$$2E = 0° \text{ (yellowish green light)}$$
$$2E = 33° 48' \text{ Tl}$$
$$n_g = 2.7414\text{Na} \quad n_m = 2.5856\text{Na} \quad n_p = 2.5832\text{Na}$$
$$n_g - n_p = 0.1582 \text{ Na}$$

Color brown, yellowish, reddish, black. In thin section pleochroism weak in yellow and brown tints; absorption formula either Z > Y > X or Y > Z > X.

OCCUR. Found rarely in cavities of igneous and metamorphic rocks, and as a secondary product in various rocks.

DIAG. The form, the enormous dispersion, the extremely high relief and the strong birefringence are characteristic of brookite.

## BRUCITE.

RHOMBOHEDRAL $c = 1.521$ $Mg(OH)_2$

PHYS. CHAR. Crystals tabular || 0001; usually foliated massive, sometimes fibrous. Cleavage || 0001 micaceous with flexible and sectile lamellæ. H. = 2.5. G. = 2.38-2.4. Soluble in acids.

OPT. PROP. Uniaxial and positive. The rings are often somewhat modified, as in biaxial crystals. Refringence moderate; birefringence rather strong.

$$n_g = 1.581 \quad n_p = 1.560$$
$$n_g - n_p = 0.021$$

Color white, often grayish or greenish. In thin section colorless or very pale greenish.

ALTER. Brucite alters to hydromagnesite; also, rarely, to serpentine.

OCCUR. Common in serpentine; also found in modified limestones; further, it is sometimes found in slates and schists.

**Pyrochroite** [$Mn(OH)_2$] resembles brucite in physical characters; in thin section it is colorless to brown and pleochroic with $Z > X$, uniaxial, and negative. Also sometimes biaxial. Refringence $n_g = 1.723$, $n_p = 1.681$; $n_g - n_p = 0.042$. Rare; associated with hausmannite.

DIAG. Brucite has better cleavage than alunite and flexible lamellæ; also wholly different occurrence and association; it differs from talc, muscovite, and gypsum in being uniaxial and positive, and from hydromagnesite in its higher birefringence.

**BRUSHITE,** see pharmacolite. **BYTOWNITE,** see feldspar group. **CABRERITE,** see vivianite.

## CALAMINE.

ORTHORHOMBIC $a : b : c :: 0.783 : 1 : 0.478$ $(ZnOH)_2SiO_3$

PHYS. CHAR. Crystals distinctly hemimorphic when doubly terminated, with pyramids at one end and the base and domes at the other. Usually somewhat elongated || $c$. Sometimes flattened || 010. Twinning on 001 rare. Often in sheaf-like aggregates; also fibrous or granular; stalactitic, massive, etc. Cleavage perfect || 110, imperfect || 101, in traces || 001. H. = 4.5-5. G. = 3.4-3.5. B.B. fuses at 6, giving a bright light. Gives reactions for Zn. Soluble in acids with gelatinization.

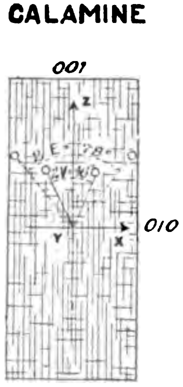


Fig. 36. Optical orientation of calamine.

OPT. PROP. The plane of the optic axes is parallel to 100; the positive acute bisectrix is normal to 001. The angle of the optic axes is rather large; axial dispersion very strong $\rho > v$, The relief is distinct, and the birefringence moderate.

$$(+)\ 2V = 46^\circ\ (2E = 81^\circ\text{Li}\ 2E = 76^\circ\text{Tl})$$

$$n_g = 1.635 \quad n_m = 1.618 \quad n_p = 1.615$$

$$n_g - n_p = 0.020 \text{ to } 0.022$$

Colorless, white, pale bluish or greenish, gray, brown. Luster vitreous.

Incl. Greenockite (CdS) has been found in fine particles included along surfaces of growth of calamine.

Occur. Commonly found in veins associated with sphalerite and smithsonite; also disseminated in limestone with zincblende, marcasite, pyrite and galena.

**Clinohedrite** [$(ZnOH)(CaOH)SiO_3$] is related chemically to calamine. It is monoclinic, with $a:b:c::0.682:1:0.323$, and $\beta = 76^\circ\ 2'$. Crystals clinohedral of varied habit. Cleavage perfect || 010. H. = 5.5. G. = 3.33. Fusible with exfoliation at 4. Gelatinizes with HCl. Optic plane and obtuse bisectrix Z normal to 010; $Y \wedge c = -28^\circ$. Birefringence not strong. Found in zinc mines with willemite, brown garnet, axinite. Very rare.

Diag. The strong dispersion, the mode of occurrence, and the crystal forms are quite characteristic.

### Calcite Group.

This is a group of carbonates of bivalent metals crystallizing in the hexagonal system. The crystals are commonly rhombohedral in aspect, but calcite has many crystal habits. Often compact, fibrous, lamellar or granular. Also stalactitic. Cleavage always very perfect parallel to the rhombohedral faces. H. = 3.-5.

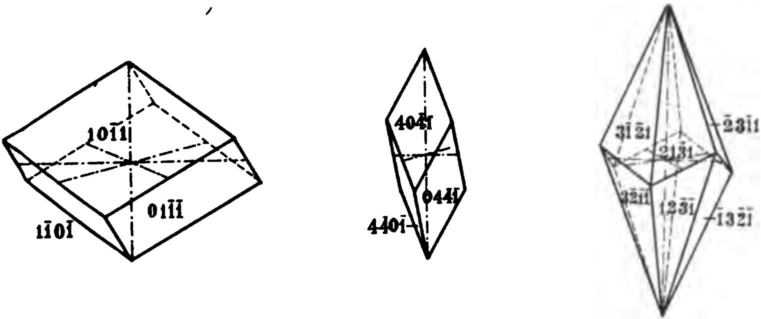
The minerals of the group are all uniaxial and negative. This group constitutes probably the best illustration of isomorphism that we have, since in chemical composition all members of the series are strictly analogous, and in physical properties are very similar, and, further, since many of the type minerals seem capable of entering into isomorphous mixtures with others in all proportions. The chief minerals of the group may be classed as follows:—

| | | | |
|---|---|---|---|
| Calcite | $c = 0.8543$ | Cleavage angle = 74° 55′ | $CaCO_3$ |
| Dolomite | $c = 0.8322$ | Cleavage angle = 73° 45′ | $(Ca,Mg)CO_3$ |
| Magnesite | $c = 0.8112$ | Cleavage angle = 72° 36′ | $MgCO_3$ |
| Siderite | $c = 0.8184$ | Cleavage angle = 73° 0′ | $FeCO_3$ |
| Rhodochrosite | $c = 0.8184$ | Cleavage angle = 73° 0′ | $MnCO_3$ |
| Smithsonite | $c = 0.8063$ | Cleavage angle = 72° 20′ | $ZnCO_3$ |

## CALCITE.

RHOMBOHEDRAL $c = 0.8543$ $CaCO_3$

PHYS. CHAR. Crystals of extreme diversity in habit, sometimes highly complex. Rhombohedral cleavage || $10\bar{1}1$ perfect. Common polysynthetic twinning with $01\bar{1}2$ as twinning plane, perhaps due in part to the grinding in making sections.



Figs. 37a, 37b, 37c. Simple crystal forms of calcite.

Occurs in rocks in anhedra or in fibrous aggregates or in concretions. H. = 4. G. = 2.72. Infusible. Easily soluble in cold dilute acids with effervescence.

OPT. PROP. Uniaxial and negative. Calcite has slight relief with very strong birefringence; it consequently shows interference colors of the light grays and greens of the fourth or higher orders even in very thin sections. Very slight differences of thickness due to imperfect polishing result in iridescent surfaces.

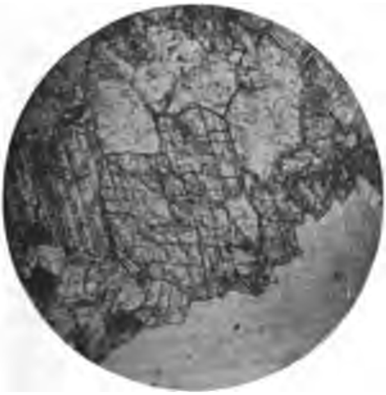


Fig. 37d. Section of calcite showing three directions of rhombohedral cleavage. Marble. U. W. 1123. One nicol. × 45.

$$n_g = 1.658 \quad n_p = 1.486$$
$$n_g - n_p = 0.172$$

Colorless, white, gray, red, green, blue, violet, yellow, brown, black. Colorless in thin section.

Occur. Not only extremely abundant in sedimentary limestone and allied rocks, but also very common in igneous rocks, where it is apparently always a decomposition product, although there are all gradations from some amphibolites, etc. to pure marble.

Diag. Low relief, rhombohedral cleavage, polysynthetic twinning parallel to rhombohedral faces, uniaxial negative character, and extremely strong birefringence are diagnostic features in thin sections. Very ready solubility in cold dilute acids, low specific gravity, common polysynthetic twinning and absence of crystal boundaries, must be relied upon chiefly to distinguish it from dolomite and other carbonates of the same group.

## DOLOMITE.

Rhombohedral $c = 0.832$ $(Ca,Mg)CO_3$

Phys. Char. Similar to calcite in physical and optical characters, but occurs even in rocks with crystal boundaries or a distinct tendency toward crystal outlines. Crystals often have slightly curved surfaces. H. = 4. G. = 2.88. Infusible. Only slowly soluble in dilute acids.

Opt. Prop. Uniaxial and negative. The refringence and birefringence increase with increase of iron content.

|  | $FeCO_3$ absent | $FeCO_3$ 3.29% | $FeCO_3$ 10.61% |
|---|---|---|---|
| $n_g =$ | 1.682 | 1.6883 | 1.7005 |
| $n_p =$ | 1.503 | 1.5070 | 1.5148 |
| $n_g - n_p =$ | 0.179 | 0.1883 | 0.1857 |

Occur. Forms rock masses of dolomitic limestone and marble; also found in limestones, phyllites, etc., as well as in occasional cavities in basic igneous rocks.

Diag. Distinguished from calcite by tendency to crystal outlines, absence of polysynthetic twinning, only slow solubility in cold acids, and higher specific gravity.

## MAGNESITE.

Rhombohedral $c = 0.811$ $MgCO_3$

Phys. Char. Similar to calcite in physical and optical characters; occurs both in crystals and as anhedra. Polysynthetic twinning is absent. Sometimes contains considerable isomorphous iron carbonate; it is then called *breunnerite* and is often yellowish in color from limonite alteration products. H. = 3.5-4.5. G. = 3.0-3.1. Infusible. Insoluble in cold acid; effervesces in warm acid.

**Opt. Prop.** Uniaxial and negative. Color white, yellowish, grayish, brown. Colorless in thin section.

$$n_g = 1.717 \quad n_p = 1.515$$
$$n_g - n_p = 0.202$$

*Breunnerite* with 16.33% $FeCO_3$, and 12.83% $MnCO_3$ is said to have weaker birefringence, with $n_g = 1.7174$. $n_p = 1.5285$, $n_g - n_p = 0.1889$.

**Occur.** Found in some chlorite and talc schists, in serpentine, etc.

**Diag.** Distinguished from calcite by absence of polysynthetic twinning; from calcite and dolomite by extremely strong birefringence, insolubility in cold acids, and higher specific gravity.

## SIDERITE.

RHOMBOHEDRAL $c = 0.818$ $FeCO_3$

PHYS. CHAR. Similar to calcite in physical and optical characters; occurs in crystals and massive. Polysynthetic twinning sometimes present. H. = 3.5-4. G. 3.83-3.88. Decrepitates, fuses at 4.5, and becomes magnetic. Soluble with effervescence in hot HCl.

OPT. PROP. Uniaxial and negative. Double refraction strong.

$$n_g = 1.873 \quad n_p = 1.633$$
$$n_g - n_p = 0.240$$

Siderite with 17.04% $MnCO_3$ and 5.42% $MgCO_3$ has $n_g = 1.9341$, $n_p = 1.6219$; $n_g - n_p = 0.3122$.

Color gray, rarely green; by alteration becomes brown to red. In thin section ashen gray to colorless; absorption often distinct.

ALTER. Changes readily on exposure, passing to limonite, and often later to hematite or magnetite.

OCCUR. Found in many sedimentary and metamorphic rocks, as limestone, clay iron stone, clay slate, mica slate, gneiss, etc. Also often associated with metallic ores in veins. Occasionally found in basic igneous rocks.

DIAG. Differs from dolomite and magnetite in common polysynthetic twinning and higher specific gravity; differs from calcite in common presence of limonite alteration products, insolubility in cold acids, and higher specific gravity. It also commonly has an ashen gray color with distinct absorption, and a high index of refraction similar to that of epidote. The indices of refraction of siderite are *both* higher than that of Canada balsam; this is not true of any other mineral of the group, except smithsonite and rhodochrosite.

## RHODOCHROSITE.

RHOMBOHEDRAL $c = 0.818$ $MnCO_3$

PHYS. CHAR. Similar to calcite. Crystals uncommon, usually massive cleavable to compact. H. = 3.5-4.5. G. = 3.45-3.60. Infusible, but decrepitates and turns black. Soluble with effervescence.

OPT. PROP. Uniaxial and negative. Double refraction strong. Indices of refraction high.

$$n_g = 1.82 \quad n_p = 1.60$$
$$n_g - n_p = 0.222$$

Color rose red, dark red, yellowish gray, brown. Streak white.

ALTER. Alters rather easily to pyrolusite.

OCCUR. Common mode of occurrence is in veins with ores of silver, lead and copper, and other ores of manganese.

DIAG. Differs from other members of the group in associated minerals, pyrolusite as an alteration product, and presence of manganese.

## SMITHSONITE.

RHOMBOHEDRAL $c = 0.806$ $ZnCO_3$

PHYS. CHAR. Similar to calcite. Crystals rare; crystal faces usually curved and rough. Often reniform, in incrustations, or granular. H. = 5. G. = 4.30-4.45. Infusible. Soluble with effervescence.

OPT. PROP. Uniaxial and negative. Double refraction strong.

$$n_g = 1.818\pm \quad n_p = 1.61766$$
$$n_g - n_p = 0.200$$

Color white, grayish, greenish, brownish, blue. Streak white.

ALTER. Alters to calamine, to quartz, or to limonite.

OCCUR. Found in veins and in beds usually associated with sphalerite and galena; also with copper and iron ores. It usually occurs in calcareous rocks, or in veins formed by carbonated waters. Often also associated with calamine.

DIAG. Differs from the other members of the group in mode of occurrence, alteration, and associated minerals. Also, chemically, in the presence of zinc.

## CALEDONITE.

ORTHORHOMBIC $a:b:c::0.916:1:1.403$ $(Pb,Cu)_2(OH)_2SO_4$

PHYS. CHAR. Crystals elongated || $a$; in divergent groups. Cleavage perfect || 001, imperfect || 100. H. = 2.5-3. G. = 6.4. Easily fusible. Soluble in part in $HNO_3$.

OPT. PROP. The optic plane is parallel to 100; the acute bisectrix X is normal to 010. $2V = 82° 37'$Li. Dispersion $\rho < v$ weak. $n_m = 1.846$ Li. Color deep green or bluish green. Streak greenish white. Pleochroic.

OCCUR. Found with lead ores chiefly in quartz veins.

## CALOMEL.

TETRAGONAL $c = 1.723$ HgCl

PHYS. CHAR. Crystals pyramidal; tabular || 001; often highly complex. Cleavage distinct || 100, indistinct || 111. H. = 1.-2. G. = 6.48. Infusible, but volatile. Soluble in aqua regia.

OPT. PROP. Uniaxial and positive. Refringence very high; birefringence twice as strong as in any other known mineral except stibnite.

$$n_g = 2.6559\text{Na} \quad n_p = 1.9732\text{Na}$$
$$n_g - n_p = 0.6827\text{Na}$$

Color white, yellowish, grayish, brown. Streak pale yellowish white.

OCCUR. Found with cinnabar in quicksilver mines. Rare.

**CANCRINITE,** see nephelite group.

## CARNALLITE.

ORTHORHOMBIC $a:b:c::0.594:1:0.691$ $KMgCl_3+6H_2O$

PHYS. CHAR. Crystals resembling hexagonal pyramids, rare. Commonly massive, granular. No distinct cleavage. H. = 1. G. = 1.6. Easily fusible. Soluble in $H_2O$. Deliquescent. Taste bitter.

OPT. PROP. The optic plane is parallel to 010; the acute bisectrix Z is normal to 100. Birefringence strong. Dispersion $\rho < v$.

$$(+)\ 2V = 69^\circ 48' \ (2E = 115^\circ 6')$$
$$n_g = 1.4937 \quad n_m = 1.4753 \quad n_p = 1.4665$$
$$n_g - n_p = 0.0272$$

Color white, often reddish metallic on account of inclusions of hematite scales. Colorless in thin section.

OCCUR. Found in salt deposits. Rare.

**Erythrosiderite** ($K_2FeCl_5 \cdot H_2O$) is also orthorhombic with $a:b:c::0.691:1:0.718$; crystals elongated || $c$, flattened || 100. Very deliquescent. Optic plane parallel to 001; acute bisectrix X normal to 100. Optic angle large ($2E > 130^\circ$); dispersion very strong with $\rho < v$. Birefringence strong. Yellow and not pleochroic in thin section. Red in mass. Found with other chlorides and with realgar and sulphur at Vesuvius.

**Chlormanganokalite** ($K_4MnCl_6$) is rhombohedral with $c = 0.58$; crystals rhombohedral without cleavage. Fracture conchoidal, glassy. H. = 2.5. G. = 2.31. Deliquescent. Readily fusible. Uniaxial and positive. (Said by Lacroix to be biaxial with small optic angle, and monoclinic.) Refringence moderate $n = 1.59$; birefringence very weak. Color yellow in mass. Formed at Vesuvius by volcanic vapors.

## CARPHOLITE.

ORTHORHOMBIC Axial ratio unknown $H_4MnAl_2Si_2O_{10}$

PHYS. CHAR. Not found in distinct crystals, but in fibrous aggregates with cleavage parallel to the elongation. H. = 5.-5.5. G. = 2.87-2.93. Not distinctly attacked by acids.

Opt. Prop. The plane of the optic axes is parallel with the elongation. The negative acute bisectrix is perpendicular to the vertical axis. The elongation is therefore positive. The angle of the optic axes is variable, but reaches:—

$$(-)\ 2V = 60^\circ \text{ about}$$

$$n = 1.63 \text{ about}$$

$$n_g - n_p = 0.022 \text{ about}$$

Color straw to wax yellow; in thin section colorless to yellow, with distinct pleochroism in the colored varieties as follows:—

Z = colorless

Y = golden yellow to colorless

X = golden yellow to colorless

The maximum absorption is therefore transverse to the elongation. The color may vary in a single crystal.

**CARPHOLITE**

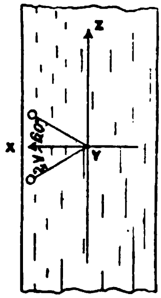


Fig. 38.
Optical orientation of carpholite.

Occur. Found rarely in quartz and metalliferous veins.

Diag. Distinguished from ardennite by positive elongation, lower relief, and fusibility.

**CARPHOSIDERITE**, see copiapite. **CASSITERITE**, see rutile group.

## CATAPLEIITE.

Hexagonal $c = 1.362$ $H_4(Na_2,Ca)ZrSi_3O_{11}$

Phys. Char. Usually thin tabular hexagonal prisms when crystallized. Twinning common of different kinds. Cleavage perfect || $10\bar{1}0$; difficult || $10\bar{1}1$ and $10\bar{1}2$. H. = 6. G. = 2.8. Soluble in acids with separation of gelatinous silica. Said by Brögger to be only pseudohexagonal and really monoclinic at ordinary temperatures.

Opt. Prop. Uniaxial and positive; but the black cross sometimes separates slightly into hyperbolas indicating an optic axial plane parallel (or nearly so) to the face $10\bar{1}1$.

$$n_g = 1.629 \quad n_p = 1.599$$

$$n_g - n_p = 0.030$$

Recent detailed study of catapleiite from Greenland by Böggild indicates that the change from monoclinic to hexagonal symmetry occurs at temperatures varying in crystals of different habit, and even in different crystals of the same habit. The temperature of transformation varies from below —50° to +220°; at ordinary temperatures most crystals are monoclinic (or orthorhombic?) with $n_g = 1.6269$, $n_m = 1.5921$, $n_p = 1.5905$, $n_g - n_p = 0.0364$, and $2V = 25^\circ 25'$, or $2E = 41^\circ 1'$. Further, in some cases, the optic plane is normal to $10\bar{1}0$.

Color light yellow to yellowish brown, grayish blue, violet. Almost colorless in thin section, but often yellowish in some parts.

Occur. Found in zircon syenites of Scandinavia.

Diag. Approximately uniaxial positive character with high relief and strong birefringence serve to identify the mineral. Also prismatic cleavage and solubility with gelatinization.

**CELADONITE,** see glauconite. **CELESTITE,** see barite group. **CELSIAN,** see feldspar group. **CERARGYRITE,** see halite group. **CERUSSITE,** see aragonite group. **CHABAZITE,** see zeolite group.

### CHALCANTHITE.

TRICLINIC $a:b:c::0.5656:1:0.5507$ $CuSO_4+5H_2O$

$\alpha=82°\ 21'$ $\beta=73°\ 11'$ $\gamma=77°\ 37'$

PHYS. CHAR. Crystals usually flattened || 111; also massive, stalactitic; sometimes fibrous. Cleavage imperfect || 110, 1$\bar{1}$0, and 111. H. = 2.5. G. = 2.12-2.30. Soluble in $H_2O$ from which iron precipitates copper.

OPT. PROP. The negative acute bisectrix is in the upper right hand rear quadrant; it therefore lies between $-a$, $+b$, and $+c$. A plane normal to this bisectrix makes an angle of 81° 31′ with 110, an angle of 43° 41′ with 1$\bar{1}$0 and an angle of 72° 52½′ with 111. The refringence is low, and the birefringence rather strong. The angle of the optic axes is considerable; dispersion $\rho < v$.

$$(-)\ 2V=56°\ 2'\ (2E=93°\ 1').$$
$$n_g=1.5464\quad n_m=1.5394\quad n_p=1.5156$$
$$n_g-n_p=0.0308$$

Color blue of various shades, sometimes greenish. Colorless in thin section.

ALTER. Varieties not compact readily fall to white powder on exposure to air.

OCCUR. Commonly formed by the oxidation and hydration of sulphide copper ores, such as chalcopyrite and chalcocite. It is therefore found in some spring waters, and in the waters of some copper mines, from which it forms stalactites. Rarely, in fibrous form in veins.

### CHALCOCITE.

ORTHORHOMBIC $a:b:c::0.5822:1:0.9701$ $Cu_2S$

PHYS. CHAR. Crystals commonly hexagonal in aspect sometimes by means of twinning on 110. Rarely elongated || $a$. Usually massive, granular to compact. Cleavage indistinct || 110. H. = 2.5-3. G. = 5.5-5.8. Fuses easily to a globule and yields copper in reducing flame. Soluble in $HNO_3$.

OPT. PROP. Opaque. Color blackish lead gray. In reflected light has metallic luster and dark lead gray color. Sometimes tarnished.

ALTER. Alters sometimes by gradual transformation to covellite (CuS); also to chalcopyrite, bornite.

OCCUR. Found in veins, and also disseminated in limestones and other rocks, associated with chalcopyrite, bornite, enargite, etc. Also produced by the action of hot springs upon copper coins.

**CHALCOPHYLLITE,** see tyrolite.

## CHALCOPYRITE.

TETRAGONAL $c = 0.985$ $CuFeS_2$

PHYS. CHAR. Crystals commonly tetrahedral in aspect, often horizontally striated. Twinning on 111, often in penetration forms; less commonly on 101, or 110. Often massive, compact. H. = 3.5-4. G. = 4.1-4.3. Fusible to magnetic globule. Soluble in $HNO_3$ with residue of S.

OPT. PROP. Opaque. Color brass yellow, often tarnished. In reflected light has metallic luster and brass yellow color. Polishes readily.

ALTER. Chalcopyrite may oxidize to a sulphate; other alteration products include malachite, chrysocolla, limonite.

OCCUR. Chalcopyrite is the most widely disseminated ore of copper. It occurs frequently in veins with other copper minerals; it is also found disseminated in crystalline schists and gneiss, and in serpentine. Less commonly it is found in igneous rocks. Finally, it is produced by the action of hot springs upon copper coins, and is sometimes formed in metallurgical furnaces.

## CHILDRENITE.

ORTHORHOMBIC $a:b:c::0.778:1:0.526$ $(Fe,Mn)Al(OH)_2PO_4+2H_2O$

PHYS. CHAR. Crystals pyramidal or prismatic. Cleavage imperfect || 100. H. = 4.5-5. G. = 3.18-3.24. Fusible at about 4 after swelling. Soluble in HCl.

OPT. PROP. The optic plane is parallel to 100. The acute bisectrix X is normal to 010. Optic angle somewhat variable; dispersion $\rho > v$, marked. $2E = 74° 25'$ Na. Color yellowish white, yellowish brown, brownish black. Streak white to yellowish.

OCCUR. Found on phyllite in slate mines; also on siderite, pyrite or quartz, sometimes with apatite or amblygonite. Rare.

**Eosphorite** differs chemically from childrenite only in containing dominant manganese instead of iron. Crystals prismatic, vertically striated; also massive. Cleavage nearly perfect || 100. H. = 5. G. = 3.11-3.15. Optically like childrenite, but $2H = 54° 30'$; dispersion $\rho < v$. Color rose pink; also yellowish, colorless, grayish, bluish. Pleochroism weak with Z pale pink to colorless, Y deep pink, X yellowish. Found in pegmatite vein with other manganese minerals. Rare.

**CHLOANTHITE,** see pyrite group. **CHONDRODITE,** see humite group.

### Chlorite Group.

PHYS. CHAR. Characterized by, and named from, the green color due to iron protoxide; but, rarely, chlorites are found with white, pink, brown or blue color. Very similar to micas, but the micaceous cleavage lamellæ, parallel to 001 are flexible, but not elastic. Distinctly monoclinic (clinochlore) or pseudo-rhombohedral and monoclinic (penninite). Twinning of different kinds is very common. H. = 2.-3. G. = 2.6-2.96. Easily attacked by acids.

OPT. PROP. Pleochroism is present in all chlorites, and the maximum absorption is always in the direction of the cleavage. The birefringence is usually very weak (penninite 0.001) only reaching 0.010 in clinochlore and 0.014 in delessite. The dispersion, on the contrary, is strong, and gives the chlorites bluish and yellowish interference colors near extinction.

OCCUR. Chlorites are very widely disseminated in nature, being found in practically all classes of rocks, and are abundant in a few. They are the only essential constituent of chlorite schist. In igneous rocks chlorite is always of secondary origin being formed at the expense of the aluminous micas, pyroxenes, amphiboles, and garnets. It is also formed by "reaction" between minerals, and may thus replace feldspars, etc.

DIAG. The chlorites are characterized by pale green color, with distinct pleochroism, low relief, weak birefringence. and strong dispersion; also by flexible but inelastic cleavage lamellæ, and absence of alkalies.

The various chlorites show relatively slight variations in their chemical composition, all of them being hydrous aluminum silicates of magnesium and iron. They are classified by Tschermak on chemical grounds as orthochlorites, which occur in crystals or large lamellæ, and leptochlorites, which occur in microscopic scaly masses. Many of the leptochlorites are too imperfectly known to merit description here. The important recognizable species are as follows:—

| | |
|---|---|
| | ORTHOCHLORITES |
| Penninite | $H_8(Mg.Fe)_5Al_2Si_3O_{18}$ |
| Clinochlore | $H_8(Mg.Fe)_5Al_2Si_3O_{18}$ |
| Ripidolite (or Prochlorite) | $H_{40}(Fe,Mg)_{23}Al_{14}Si_{13}O_{90}$ |
| Corundophilite | $H_{20}(Mg,Fe)_{11}Al_8Si_6O_{45}$ |
| | LEPTOCHLORITES |
| Delessite | $H_{10}(Fe,Mg)_4(Al.Fe)_4Si_4O_{23}$ |
| Ærinite | Composition? |

## PENNINITE.

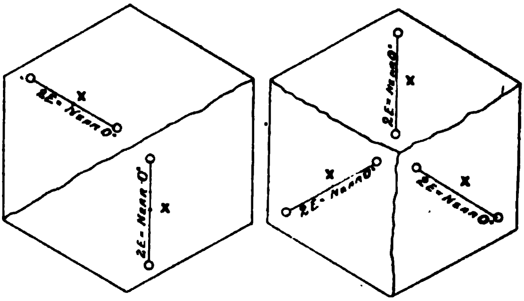
MONOCLINIC PSEUDORHOMBOHEDRAL $H_8(Mg,Fe)_5Al_2Si_3O_{18}$

$a:b:c::0.577:1:2.277$

$\beta = 89° 40'$

PHYS. CHAR. Usually in thin lamellæ which are sometimes triangular or hexagonal; sometimes fibrous. Perfect basal 001 cleavage, producing flexible inelastic lamallæ. Percussion and pressure figures are like those in mica. Twinning according to the penninite law, in which the twinning plane is the basal plane, which is also the composition face; and also according to the mica law, in which the twinning plane is perpendicular to the base and lies in the zone of 001 and 110; in this case also the composition face is often the basal plane. In the first type there is rotation of 180° about the twinning axis; in the second case the rotation is 60° or a multiple of 60°. H. = 2.-2.5. G. = 2.6-2.84. Fusible with difficulty after exfoliation. Decomposed by $H_2SO_4$.

Opt. Prop. The acute bisectrix which is perpendicular to the base 001 is usually negative. The mineral often gives



**Figs. 39 and 40. Diagrams of basal sections of penninite showing two types of grouping of laminæ twinned on the mica law.**

the interference figure of a uniaxial species on account of the combined effect of the numerous submicroscopic twinning individuals. The optic axial angle is never large. Strong dispersion with $\rho > v$ in negative crystals, and $\rho < v$ in positive crystals.

$$(\pm)\ 2E \text{ usually nearly } 0^\circ$$

$$n_g = 1.579 \quad n_p = 1.576$$

$$n_g - n_p = 0.001 \text{ to } 0.003$$

The polarization colors are very characteristic, being in the grayish blue of the first order for sections of 0.02 to 0.03 mm. thickness. In ordinary light there is no extinction on account of the strong dispersion; instead, the color is a darker blue, changing to "ultra blue" in one direction and pale yellowish in the other.

Color green of various shades; rarely red, violet, pink, yellow, white. The pleochroism is distinct and becomes stronger as one deals with varieties more deeply colored. The minimum absorption always occurs in the directions perpendicular to the base; therefore we have*:—

| Penninite — | Penninite + |
|---|---|
| Z = green | very pale yellowish green to colorless |
| Y = green | green |
| X = very pale yellowish green to colorless | green |

The absorption is therefore as follows:—

Penninite — $Z = Y > X$

Penninite + $Z < Y = X$

The elongation of the common negative penninite is positive with extinction sensibly parallel.

Occur. Penninite is a very common alteration product; it is often formed from biotite, less commonly from amphibole, pyroxene, garnet, or even feldspar. It occurs in veins, in rock cavities, and in all kinds of rocks.

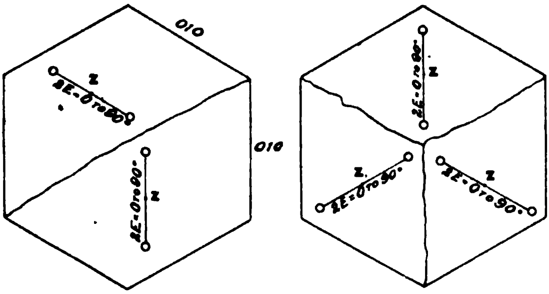
Diag. The distinguishing characters of penninite are its pale green color and pleochroism, generally negative sign, nearly uniaxial character, and very weak birefringence.

## CLINOCHLORE.

Monoclinic $a:b:c::0.577:1:2.277$ $H_8(Mg,Fe)_5Al_2Si_3O_{18}$

$\beta = 89° 40'$

Phys. Char. Similar to penninite in physical characters and composition. Microscopic crystals more abundant.



Figs. 41 and 42. Diagrams of basal sections of clinochlore showing two types of grouping of laminæ twinned on the mica law.

Polysynthetic twinning common. H. = 2.-2.5. G. = 2.65-2.78. Fusible with difficulty. Decomposed by $H_2SO_4$.

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* See Gabbroid Rocks of Minnesota. A. N. Winchell. *American Geologist*, Vol. XXVI. p. 350.

OPT. PROP. The plane of the optic axes is usually parallel to 010, and the acute bisectrix, which is ordinarily positive, is nearly perpendicular to 001. According to Tschermak it makes an angle of 2° 30′ with the normal to 001. The angle of the optic axes is quite variable, even in a single lamella, but it is distinctly larger than in penninite except in colorless clinochlore. Weak inclined dispersion with $\rho < v$.

$$(+)\ 2E = 0^\circ, 26^\circ, 44^\circ, 72^\circ, \text{etc.}$$

$$n_g = 1.596 \quad n_m = 1.588 \quad n_p = 1.585$$

$$n_g - n_p = 0.011$$

Fine twinning bands common in thin sections.

Color dark grass green to olive green; rarely yellowish, white, rose red. Pleochroism is always distinct, except in the rare uncolored varieties, as follows:—

c Z = pale yellowish green to colorless
b Y = pale green
a X = pale green

The absorption formula is X > Y > Z.

OCCUR. Very widely distributed, but not as abundant as penninite as a microscopic constituent of all classes of rocks.

DIAG. Characterized by pale green color and pleochroism, generally positive and distinctly biaxial character, notable birefringence and common polysynthetic twinning bands, often with perceptible extinction angles.

### RIPIDOLITE (Prochlorite).

MONOCLINIC $a:b:c::0.577:1:2.277$ $H_{40}(Fe,Mg)_{23}Al_{14}Si_{15}O_{90}$

$$\beta = 89^\circ\ 40'$$

PHYS. CHAR. Similar to penninite in physical and optical characters, but usually occurs in interlaced lamellæ, or more rarely in vermiculate prisms, or in rosettes, or spheroidal groups. H. = 1.-2. G. = 2.78-2.96. Fusible with difficulty. Decomposed by $H_2SO_4$.

OPT. PROP. The acute bisectrix which is usually positive is inclined about 2° from the normal to 001. The birefringence seems to be similar to that of penninite, and the dispersion is also very strong, with $\rho < v$. The angle of the optic axes is small and often almost zero.

Color usually green, rarely bronze brown or greenish gray. The pleochroism is distinct as follows:

Z = colorless or greenish yellow or brownish
Y = green, yellowish green
X = green, yellowish green

OCCUR. Found in the same rocks as the other chlorites, as an alteration product in eruptive and metamorphic rocks, and as an essential of some crystalline schists. But it occurs in the purest masses in veins in these rocks, associated with quartz, orthoclase, albite, rutile, octahedrite, titanite, ilmenite, etc. It often occurs in poikilitic growths in orthoclase, albite, quartz, calcite, axinite, prehnite, etc.

DIAG. Distinguished from penninite by its vermiculate forms, its usual positive character, its greater content of iron, and its greater specific gravity.

## CORUNDOPHILITE.

MONOCLINIC $a:b:c::0.577:1:2.277$ $H_{20}(Fe,Mg)_{11}Al_8Si_6O_{45}$

$\beta = 89° 40'$

PHYS. CHAR. Similar to penninite. Usually in six-sided or twelve-sided tables or low prisms. Laminæ somewhat more brittle than those of penninite. H. = 2.5. G. = 2.90.

OPT. PROP. The plane of the optic axes is parallel to 010, and the positive acute bisectrix is inclined 8° to the normal to 001. Dispersion $\rho < v$ distinct. Color green.

$(+)\ 2E = \text{variable, e. g. } 65°, 80°.$

$n_m = 1.583$ about

OCCUR. Always found associated with corundum or emery. Rare.

DIAG. Distinguished from penninite and ripidolite by rather large optic angle; from all other chlorites by association with corundum.

## DELESSITE.

MONOCLINIC? Axial ratio unknown $H_{10}(Fe,Mg)_4(Al,Fe)_4Si_4O_{23}$

PHYS. CHAR. Resembles penninite in physical characters, but occurs in lamellar masses, rosettes or spherulites without crystal outlines. H. = 2.-3. G. = 2.6-2.9. Fusible with difficulty. Easily soluble in acids with residue of silica.

OPT. PROP. The acute negative bisectrix is sensibly normal to the micaceous cleavage 001. The angle of the optic axes is nearly zero.

$(-)\ 2E = 0° +$

$n = 1.619$ about

$n_g - n_p = 0.014$ about

Color usually green, rarely pink. The pleochroism is always distinct, as follows:—

| Green delessite | Pink delessite |
|---|---|
| Z = green | pink |
| Y = green | pink |
| X = pale green or colorless | pale yellow or colorless |

OCCUR. Very common alteration product of old basic igneous rocks, though only sparsely distributed. Also found filling cavities in altered felsitic rocks.

DIAG. Distinguished from the other chlorites by its stronger birefringence.

## ÆRINITE.

MONOCLINIC? Axial ratio unknown Formula unknown

COMP. Ærinite is a hydrous silicate of aluminum and other bases, probably including iron, calcium and magnesium.

Phys. Char. Crystals unknown; usually compact fibrous to lamellar. Cleavage perfect || 001. G. = 2.48. Gives water and turns to wood brown color in the closed tube. Easily fusible. Soluble even in cold acids.

Opt. Prop. The negative acute bisectrix is nearly normal to the micaceous cleavage 001. The direction of the elongation of the fibers is therefore positive. The optic angle is small; the dispersion is very strong, like that of penninite. The fibers and lamellæ are often interlaced.

Color blue; pleochroism intense in thin section with Z = Y = dark cobalt blue, X = yellowish or colorless.

Occur. Found in veins in altered diabase. Rare.

Diag. The micaceous character with intense blue pleochroism is quite characteristic.

### Chloritoid Group.

Triclinic or monoclinic (Pseudohexagonal) $H_2FeAl_2SiO_7$

Axial ratio unknown

Comp. It is still somewhat uncertain whether the minerals included here form a group or should be considered simply as varieties of a single species. This uncertainty is largely due to the fact that inclusions are so abundant as to prevent securing pure material for analysis. The optical properties of these minerals are the same, or at least very similar. The formula given above corresponds approximately with the analysis of *chloritoid* (proper) and *sismondine*. Magnesium may replace part of the iron. *Venasquite* contains much more silica; *ottrelite* is rich in silica and also contains some MnO replacing part of the FeO.

Phys. Char. Similar to micas in form; also twinned according to the mica law in which the twinning plane is perpendicular to the base and lies in the zone of 001 and 110. The composition face is usually the base, but may vary in a single mass, or the individuals may interpenetrate irregularly. Twinning usually polysynthetic. Basal cleavage not as good as in the micas, although accentuated by twinning. Difficult cleavages parallel to 110 and 1$\bar{1}$0, almost perpendicular to 001, and forming an angle near 120°. Finally, a cleavage or parting parallel to 010 which approximately bisects the obtuse angle of the prismatic cleavages. Cleavage lamellæ are not flexible. H. = 6.5. G. = 3.26-3.57. Nearly infusible, but becomes magnetic. Decomposed by $H_2SO_4$.

Opt. Prop. The plane of the optic axes is parallel, or almost parallel, to 010. The positive acute bisectrix makes an angle with the vertical axis of about 3° in some cases, 12° to 18° in others, and in exceptional cases 28°. This angle is large in *ottrelite*. The angle of the optic axes varies in different localities. The dispersion is very

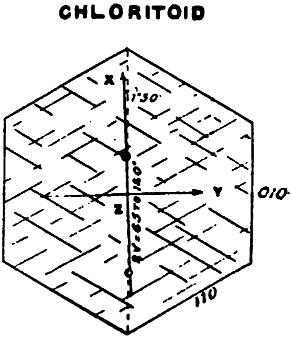


Fig. 43. Optical orientation of chloritoid.

strong, with $\rho > v$, and notable horizontal dispersion, but this is less in some occurrences.

$$(+)\ 2E = 65° \text{ to } 120°$$
$$n_m = 1.741$$
$$n_g - n_p = 0.010 \text{ about } (0.007 \text{ to } 0.016)$$

Color dark gray to greenish black. The pleochroism is very strong and characteristic. It varies in intensity in different localities, but is always:

Z = greenish yellow
Y = indigo blue
X = olive green

INCL. Usually rich in inclusions, especially of grains of quartz, but also of magnetite, ilmenite, rutile, tourmaline; and in *ottrelite* carbonaceous matter, which is sometimes regularly distributed.

ALTER. Alters to muscovite and penninite.

OCCUR. Found only in crystalline schists where it is sometimes very abundant.

DIAG. Color, pleochroism, high relief, weak birefringence, large optic angle (cf. chlorites), and strong dispersion are quite characteristic. The cleavages are numerous but not micaceous; the cleavage lamellæ are not elastic nor flexible; the specific gravity is high.

## CHLOROPAL.

MONOCLINIC? Axial ratio unknown $H_6Fe_2(SiO_4)_3+2H_2O$?

PHYS. CHAR. Compact massive, resembling opal; also earthy. Often composed of microscopic laminæ in radiating aggregates. Cleavage distinct, parallel to the lamination 001; also parallel to a prism 110 at an angle of 63°-64°. More or less hygroscopic. Feel soapy to meager. H. = 1.-2. in variety *nontronite*; 2.5-4.5 in other varieties. G. = 2.1-2.35. Gives water in the closed tube. Infusible. Partially or completely decomposed by HCl.

OPT. PROP. The negative acute bisectrix is normal or nearly normal to the lamination; the elongation is always positive. The birefringence is strong, $n_g - n_p = 0.020$ at least. The angle of the optic axes is moderate, $2E = 55° \pm$.

Color straw yellow to greenish. In thin section the pleochroism is perceptible with Z = Y = yellow to greenish yellow, X = pale yellow to colorless.

OCCUR. Chloropal is an alteration product found in some mineral veins, in fractures in granite rocks, and in sedimentary rocks. Rare.

**CHROMITE,** see spinel group.

## CHRYSOBERYL (Cymophane).

ORTHORHOMBIC $a:b:c::0.470:1:0.580$ $BeAl_2O_4$

PHYS. CHAR. The axes $a$ and $c$ are reversed by some authors. Cleavage imperfect parallel to 011 and 010. Twinning on 031 both contact and penetration; often cyclic giving pseudohexagonal forms. H. = 8.5. G. = 3.5-3.84. Infusible. Insoluble in acids.

Opt. Prop. The plane of the optic axes is parallel to 010; the positive acute bisectrix is perpendicular to 001. Dispersion $\rho > v$. Heat causes the optic axes to come together and then open again in a plane parallel to 001.

$$(+)\ 2E = 84^\circ\ 43'\ (2V = 45^\circ\ 20')$$
$$n_g = 1.756 \quad n_m = 1.748 \quad n_p = 1.747$$
$$n_g - n_p = 0.009$$

Color green of various shades, yellow, brown. Colorless in thin section. Pleochroic in very thick sections as follows:—

Z = emerald green
Y = orange yellow
X = columbine red

Occur. Rare. Found in mica slate in the Ural mountains; in alluvial deposits in Brazil and Ceylon; in granite in New England.

**CHRYSOBERYL**

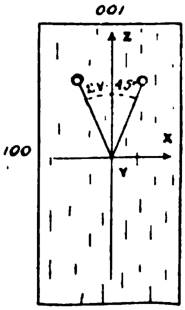


Fig. 44.
Optical orientation of chrysoberyl.

Diag. Very high relief with weak birefringence; high hardness and specific gravity; infusibility and insolubility.

**CHRYSOLITE**, see olivine group. **CHRYSOTILE**, see serpentine group.

### Cinnabar Group.

The minerals of the cinnabar group crystallize in the hexagonal system; they are simple sulphides (or arsenides, antimonides) of mercury, copper, cadmium, zinc, nickel or iron. The crystal forms differ somewhat; some of the series are trapezohedral, and others are simple hexagonal. The hardness ranges from 2 to 4, and the density from 4 to 8.

The minerals of the group are the following:—

| | | |
|---|---|---|
| Cinnabar | $c = 1.1453$ | $HgS$ |
| Covellite | $c = 1.1466$ | $CuS$ |
| Greenockite | $c = 0.9364$ or $0.8109$ | $CdS$ |
| Wurtzite | $c = 0.9440$ or $0.8175$ | $ZnS$ |
| Millerite | $c = 0.9883$ | $NiS$ |
| Niccolite | $c = 0.9462$ or $0.8194$ | $NiAs$ |
| Breithauptite | $c = 0.9915$ or $0.8586$ | $NiSb$ |
| Pyrrhotite | $c = 1.0047$ or $0.8701$ | $Fe_nS_{n+1}$ |

### CINNABAR.

Hexagonal $c = 1.1453$ $HgS$

Phys. Char. Crystals usually thick, tabular or rhombohedral in habit; trapezohedral faces rare; sometimes prismatic, acicular. Twinning on 0001, often interpenetrated; also on $11\bar{2}0$. In crystalline crusts; also granular to earthy. Cleavage perfect || $10\bar{1}0$. H. = 2.-2.5. G. = 8.0-8.2. Wholly volatile before the blowpipe.

Opt. Prop. Uniaxial and positive. The refringence is extraordinarily high; the birefringence extremely strong; and the dispersion is remarkably great. Cinnabar produces circular polarization.

$$n_g = 3.201 \text{ Li} \quad n_p = 2.854 \text{ Li}$$
$$n_g - n_p = 0.347.$$

Color bright red, brownish red, grayish red. Streak scarlet. Luster adamantine.

Occur. Occurs chiefly in veins in shales and slates; rarely in veins in igneous rocks; it is sometimes formed as a result of solfataric action about hot springs. It is often associated with pyrite, marcasite, stibnite, realgar, calcite, quartz, opal, barite, fluorite, and bituminous material.

Diag. The optical properties are quite characteristic. Also distinguished by its red color and volatility.

## COVELLITE.

Hexagonal $c = 1.1466$ CuS

Phys. Char. Rare in hexagonal crystals horizontally striated. Usually massive. Cleavage perfect || 0001; flexible in thin laminæ. H. = 1.5-2. G. = 4.59-4.63. B.B. burns, giving off $SO_2$, and fuses to a globule.

Opt. Prop. Opaque. The deep indigo blue color in reflected light is distinctive, together with a submetallic, somewhat resinous luster.

Occur. Associated with other copper ores, as chalcocite and chalcopyrite. Sometimes derived from the alteration of chalcocite. Rare.

## GREENOCKITE.

Hexagonal $c = 0.8109$ CdS

Phys. Char. Crystals hemimorphic, short prismatic; commonly in crusts; earthy. Cleavage distinct || $11\bar{2}0$, indistinct || 0001. H. = 3.-3.5. G. = 4.9-5. Gives a reddish brown coating in the reducing flame. Soluble in HCl.

Opt. Prop. Uniaxial and positive. The refringence is extremely high, but the birefringence is weak. $n_p = 2.688$. Color yellow of various shades.

Occur. Found in cavities in basic igneous rocks with prehnite, but more common in regions of zinc ores in small amounts, coloring smithsonite or coating sphalerite. Rare.

## WURTZITE.

Hexagonal $c = 0.8175$ ZnS

Phys. Char. Crystals hemimorphic, short prismatic or pyramidal in aspect. Also finely fibrous or columnar, massive. Cleavage easy || $11\bar{2}0$, difficult || 0001. H. = 3.5-4. G. = 3.98. Difficultly fusible, giving a zinc coating. Soluble in HCl.

Opt. Prop. Uniaxial and positive. Refringence high; birefringence weak; $n_g - n_p = 0.020$. Commonly lamellar parallel 0001 to fibrous with negative elongation. Color brownish black. Luster resinous. Feebly pleochroic in yellow tints, with X > Z.

Occur. Found with other zinc ores and with copper and silver ores in veins. Rare.

Diag. Distinguishable only by the optical properties from sphalerite when crystal form is lacking.

## MILLERITE.

Hexagonal $c = 0.9883$ NiS

Phys. Char. Usually in acicular to capillary crystals (of rhombohedral symmetry) often in radiating tufts; also in fibrous coatings. Cleavage perfect || $10\bar{1}6$, $01\bar{1}6$, 1013, and $01\bar{1}3$. H. = 3.-3.5. G. = 5.3-5.65. Fuses to a globule B.B. Reacts for Ni; also often traces of Co, Cu, and Fe.

Opt. Prop. Opaque. Color brass yellow to bronze yellow, often with gray iridescent tarnish. Streak greeenish black. Luster metallic and color pale brass yellow in reflected light.

Occur. Found in cavities in veins; also in geodes in limestone with calcite, dolomite and fluorite.

**Niccolite** (NiAs) is closely related to millerite. Crystals rare; usually massive, also reticulated. H. = 5.-5.5. G. = 7.33-7.67. Fusible. Color pale copper red, with dark gray tarnish. Opaque with metallic luster. Soluble in aqua regia. Found in veins with cobalt, silver and copper ores. Rare.

**Breithauptite** (NiSb) is related to niccolite. Crystals thin tabular hexagonal; also arborescent or massive. H. = 5.5. G. = 7.54. Color light copper red with tinge of violet. Luster metallic, splendent. Streak reddish brown. Opaque. Found in veins with calcite, galena, and smaltite. Very rare.

## PYRRHOTITE.

Hexagonal $c = 0.8701$ $Fe_nS_{n+1}$

Phys. Char. Crystals usually hexagonal prisms either elongated || $c$ or in flat tablets. The mineral usually occurs in compact masses more or less granular. Twinning plane || $10\bar{1}1$ produces twins with the vertical axes nearly at right angles. Cleavage sometimes distinct || 0001, difficult || $11\bar{2}0$. H. = 3.5-4.5. G. = 4.6 (pyrrhotite) to 4.8 (troilite). Unchanged in the closed tube. Gives off sulphur in the open tube. Fusible to black magnetic mass. Soluble in HCl with liberation of $H_2S$. Pyrrhotite is magnetic, but to a very variable degree.

Opt. Prop. Opaque. Color between bronze yellow and copper red, darker than pyrite, subject to tarnish. Luster metallic. Streak grayish black. Cleavage usually not visible microscopically. Too brittle to take a good polish. Attacked by hot HCl (1 part in 1 part $H_2O$), while pentlandite is not.

OCCUR. Pyrrhotite is found in basic igneous rocks, and much more rarely in acid types, especially nepheline rocks. It also occurs in amphibolites and crystalline schists. Further, it is found in rocks produced by contact metamorphism. But the largest masses and best crystals are found in metalliferous veins. Finally, it occurs in meteorites; in stony meteorites pyrrhotite occurs, in iron meteorites *troilite* occurs. Troilite has the composition FeS. It is possible that these two are identical; they are certainly closely related.

DIAG. Distinguished from pyrite by the color, the crystal form. the density, the magnetism, and the attack by HCl. Distinguished from pentlandite by etching with HCl.

**CLAUDETITE,** see valentinite. **CLINOCHLORE,** see chlorite group.

## CLINOCLASITE.

MONOCLINIC $a:b:c::1.907::1:3.851$ $Cu_3(OH)_3AsO_4$

$\beta = 80° \ 30'$

PHYS. CHAR. Crystals prismatic, elongated || *b* or tabular || 001. Often roughly grouped; also spherical, reniform, fibrous, massive. Cleavage perfect || 001. H. = 2.5-3. G = 4.19-4.36. Fusible at 2 with bluish green flame color. Soluble in $HNO_3$.

OPT. PROP. The optic plane is parallel to 010; the acute bisectrix X makes an angle of about +10° with *c*. Optic angle large; slight inclined dispersion with $\rho < v$ very strong.

$(-) \ 2E = 134° \text{ to } 141° \ Tl$

Color blackish blue-green on the surface, dark green to sky blue inside. Streak bluish green. Luster bright.

OCCUR. Found with copper ores often in cavities in quartz crystals. Rare.

**CLINOHEDRITE,** see calamine. **CLINOHUMITE,** see humite group.

## Clintonite Group.

MONOCLINIC $m(H_2CaMg_4Si_3O_{12})+n(H_2CaMgAl_6O_{12})$

COMP. Chemically there is a series of minerals quite closely related which beginning with the micas pass through margarite, the clintonites, and the chloritoids to the chlorites. All of these minerals except the micas and the chlorites are sometimes grouped together as the *brittle micas* because their cleavage lamellæ possess neither elasticity nor flexibility. All the brittle micas are sometimes placed in the clintonite group in a wider sense than here used.

Phys. Char. Micaceous basal cleavage giving brittle lamellæ. Twinning according to the mica law. Percussion and pressure figures like those of the micas, but reversed in position so that the pressure figures are parallel and the percussion figures perpendicular to the hexagonal faces. G. = 3.0-3.1.

The minerals belonging to the group are as follows:—

| | |
|---|---|
| Xanthophyllite | $H_8(Mg,Ca)_{14}Al_{16}Si_5O_{52}$ ? |
| Brandisite | $H_5(Mg,Ca)_8Al_8Si_3O_{28}$ ? |
| Seybertite | $H_3(Mg,Ca)_5Al_5Si_2O_{18}$ ? |

## XANTHOPHYLLITE.

Monoclinic $a:b:c::0.577:1:3.244$ $\beta=90°$ $H_8(Mg,Ca)_{14}Al_{16}Si_5O_{52}$ ?

Phys. Char. Parameters almost the same as those of biotite. Micaceous basal cleavage with brittle lamellæ. Twinning according to the mica law usually polysynthetic. Usually in tabular crystals simulating the rhombohedron and base. Percussion and pressure figures interchanged in position as compared with the micas. H. = 4.5 on 001 and 5.5 on other faces. G. = 3.0-3.1. Infusible.

Opt. Prop. The plane of the optic axes is parallel to 010; the negative acute bisectrix is sensibly perpendicular to 001—varies 32′ from perpendicular position. The apparent elongation is positive with sensibly parallel extinction. Weak dispersion with $\rho < v$. The angle of the optic axes is somewhat variable, but not large.

$$(-)\ 2E = 17° \text{ to } 32°$$

$$n_g = 1.661 \quad n_m = 1.660 \quad n_p = 1.649$$

$$n_g - n_p = 0.012$$

Color leek to bottle green. Pleochroism usually weak in thin section as follows:

Z = green
Y = green
X = reddish brown

Occur. Found in chlorite schists in the Ural mountains.

Diag. Brittle cleavage laminæ, the position of the percussion and pressure figures, the hardness and the infusibility distinguish this mineral from biotite and chlorite. Differs from chloritoid in pleochroism, negative sign and small optic angle. Very similar to brandisite.

## BRANDISITE.

Monoclinic $H_5(Mg,Ca)_8Al_8Si_3O_{28}$ ?

Phys. Char. Similar to xanthophyllite in physical characters Usually in short hexagonal prisms limited by basal planes. G. = 3.0-3.1. H. = 5. on the base; 6.+ on other faces. Infusible.

Opt. Prop. The plane of the optic axes is parallel to 010; the negative acute bisectrix is sensibly perpendicular to 001. The angle of the optic axes is small. The apparent elongation is positive with sensibly parallel extinction. Birefringence moderate. Weak dispersion with $\rho < v$.

$(-)2E = 18° \text{ to } 35°$

Color yellowish to dark green, rarely reddish gray. Colorless in thin section; in thick sections pleochroism as follows:—

$Z =$ green
$Y =$ green
$X =$ brown

Occur. Only known in certain contact rocks of Tyrol.

Diag. Brittle cleavage laminæ, the position of the percussion and pressure figures, hardness and infusibility distinguish this mineral from biotite and chlorite. Weaker birefringence than biotite. Differs from chloritoid in absence of pleochroism, negative sign and small optic angle. Very similar to xanthophyllite.

**BRANDISITE**

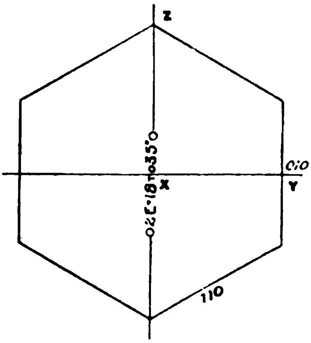


Fig. 45. Optical orientation of brandisite.

## SEYBERTITE.

Monoclinic $H_3(Mg,Ca)_5Al_5Si_2O_{18}$ ?

Phys. Char. Similar to xanthophyllite in physical characters. H. = 4.-5. G. = 3.0-3.15. Infusible.

Opt. Prop. The plane of the optic axes is perpendicular to 010· the negative acute bisectrix is nearly perpendicular to 001. The apparent elongation is positive with sensibly parallel extinction. The angle of the optic axes is small, but variable. Weak dispersion with $\rho < v$.

$(-)\ 2E = 0° \text{ to } 20°$

$n_g = 1.658 \quad n_m = 1.657 \quad n_p = 1.646$

$n_g - n_p = 0.021$

Color reddish brown, yellowish, copper red. Luster pearly submetallic. The pleochroism is rather weak in section, as follows:—

$Z =$ pale brownish yellow
$Y =$ pale brownish yellow
$X =$ colorless

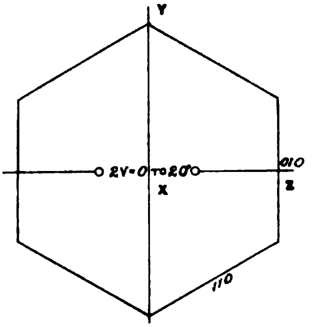


Fig. 46. Optical orientation of seybertite.

Occur. Found in Orange Co., N. Y. in limestone with serpentine.

Diag. Similar to brandisite in distinguishing characters. Differs from xanthophyllite and brandisite in the position of the optic plane, in small optic angle, and in pleochroic colors.

**COBALTITE,** see pyrite group.

## COLEMANITE.

MONOCLINIC $a:b:c::0.7748:1:0.541$ $Ca_2B_6O_{11}+5H_2O$

$\beta = 69° \ 51'$

PHYS. CHAR. Crystals usually short prismatic, highly modified; also in forms resembling acute rhombohedrons. Massive cleavable to granular and compact. Cleavage perfect || 010, distinct || 001. H. = 4.-4.5. G. = 2.42. Decrepitates, exfoliates, and fuses in part with yellowish green flame color. Soluble in hot HCl.

OPT. PROP. The plane of the optic axes and the obtuse bisectrix are normal to 010; the positive acute bisectrix makes an angle of 83° with $c$. The refringence is moderate, and the birefringence strong. The angle of the optic axes is rather large; dispersion weak, $\rho < v$.

$$(+) \ 2V = 55° \ 20' \ (2E = 95° \ 15')$$

$$n_g = 1.61398\text{Na} \quad n_m = 1.59202\text{Na} \quad n_p = 1.58626\text{Na}$$

$$n_g - n_p = 0.02772$$

Colorless to white, yellowish, gray. Luster vitreous to adamantine. Colorless in section.

OCCUR. Found in arid regions in California with quartz and strontianite. Rare.

**COLUMBITE**, see stibiotantalite. **COPPER**, see gold group.

## COPIAPITE.

MONOCLINIC $a:b:c::0.479:1:0.975$ $Fe_4S_5O_{21}+18H_2O$

$\beta = 72° \ 3'$

PHYS. CHAR. Crystals tabular || 010; usually lamellar aggregates, or massive. Cleavage || 010. H. = 2.5. G. = 2.1. Soluble in cold $H_2O$; heating causes precipitation of iron.

OPT. PROP. The optic plane is normal to 010 and nearly parallel to $\bar{4}09$; the acute bisectrix X is normal to 010. The optic angle is very large. $2V = 90° \pm$. $(2H = 111° \ 36'-114° \ 15')$. $n_g = 1.572$, $n_m = 1.547$, $n_p = 1.527$, $n_g - n_p = 0.052$.

Color sulphur to citron yellow. Luster pearly. Pleochroic in thick plates, pale yellow to colorless.

OCCUR. Found with copper and iron vitriols; usually produced by the oxidation of iron sulphide. Rare.

**Amarantite** $(Fe_2S_2O_9+7H_2O)$ is chemically related to copiapite, but it is triclinic with $a:b:c::0.769:1:0.574$ and $\alpha = 95° \ 38'$, $\beta = 90° \ 24'$ and $\gamma = 97° \ 13'$. Crystals long, prismatic, vertically striated; in columnar or bladed masses. Cleavage perfect || 100 and 010. H. = 2.5. G. = 2.11-2.29. Slowly decomposed, but insoluble in cold $H_2O$. Optic plane inclined about 38° to $c$; extinction in the + direction on 100; on 010 —16° to —17° on $c$. Acute bisectrix X approximately normal to 100; $2E = 63° \pm$ Na. Dispersion $\rho < v$, strong. Color orange red, brownish red; pleochroism of crystals weak on 100, distinct on 010, brownish red to lemon yellow. Found with galena, sphalerite, chalcopyrite in copiapite. Rare.

**Carphosiderite** ($Fe_6S_4O_{21} + 10H_2O$) is chemically related to copiapite, but is apparently rhombohedral. Usually in reniform masses and incrustation; also lamellar. Basal cleavage perfect. H. = 4-4.5. G. = 2.49-2.73. Feel greasy. Insoluble in $H_2O$; soluble in HCl. Uniaxial and positive. Birefringence strong. Color pale to deep straw yellow. Luster resinous. Found in fissures in slate and sandstone, probably from oxidation of iron sulphide. Very rare.

## COQUIMBITE.

RHOMBOHEDRAL $c = 1.561$ $Fe_2(SO_4)_3 + 9H_2O$

PHYS. CHAR. Crystals short prismatic, or rhombohedral. Also granular massive. Twinning on 001. Cleavage imperfect || $10\bar{1}0$, $10\bar{1}1$, and $01\bar{1}1$. H. = 2.-2.5 G. = 2.1. Soluble in cold $H_2O$; heat precipitates iron. Taste astringent.

OPT. PROP. Uniaxial and positive. Refringence low.

$$n_g = 1.5547 \quad n_p = 1.5455$$

$$n_g - n_p = 0.0092$$

Color, white, yellowish, brownish, greenish, amethystine.

OCCUR. Found in large masses in a feldspathic rock, apparently produced by the decomposition of sulphides; also reported about volcanoes. Rare.

**Quenstedtite** [$Fe_2(SO_4)_3 + 10H_2O$] is chemically related to coquimbite, but it is monoclinic, with $a:b:c::0.394:1:0.406$ and $\beta = 78°$ 8′. Crystals like gypsum. Cleavage perfect || 010; imperfect || 100 or 110. H. = 2.5. G. = 2.12. Soluble in $H_2O$. Optic plane parallel to 010; $X \wedge c = +21°$. Color reddish violet. Luster vitreous. Found with coquimbite. Rare.

## CORDIERITE (Iolite).

ORTH. $a:b:c::0.5871:1:0.5585$ $H_2(Mg,Fe)_4Al_8Si_{10}O_{37}$

PHYS. CHAR. Crystals usually short prismatic with basal plane prominent; often twinned to produce pseudohex-

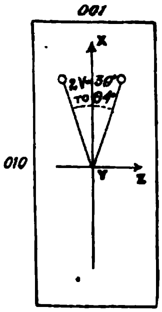
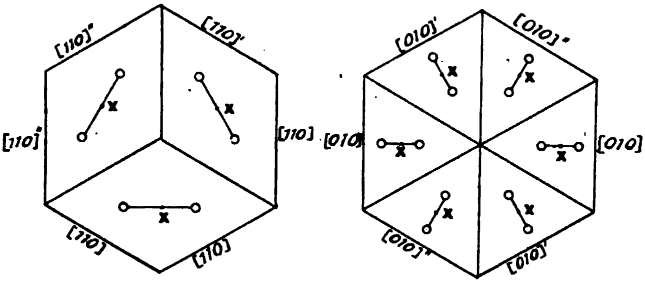


Fig. 47. Optical orientation of cordierite.



Figs. 48 and 49. Diagrams of basal sections of cordierite showing two modes of grouping to produce pseudohexagonal forms through twinning on 110.

agonal forms; also massive. Cleavage distinct parallel to 010, indistinct parallel to 100 and 001. When partially altered the mineral becomes lamellar parallel to 001. Twinning* with the twinning plane parallel to 110 or 130 often repeated to produce pseudohexagonal forms; sometimes producing polysynthetic bands as in plagioclase. H. = 7.-7.5. G. = 2.60-2.66. Fusible at 5.5. Partly decomposed by acids.

Opt. Prop. The plane of the optic axes is parallel to 100; the negative acute bisectrix is perpendicular to 001. The dispersion is weak, with $\rho < v$. The angle of the optic axes is quite variable in different crystals, and may even vary in different parts of a single crystal. Heat increases the optic angle very perceptibly. The indices of refraction also vary in cordierite of different localities.

$(-)\ 2V = 39^\circ$ to $84^\circ$ about

| | Haddam, Ct. | Ceylon | Bodenmais | Orijarvi |
|---|---|---|---|---|
| $n_g =$ | 1.563 | 1.543 | 1.546 | 1.540 |
| $n_m =$ | 1.562 | 1.542 | 1.541 | 1.538 |
| $n_p =$ | 1.552 | 1.537 | 1.535 | 1.534 |
| $n_g - n_p =$ | 0.011 | 0.006 | 0.011 | 0.006 |
| $2V =$ | 39° 32′ | 70° 23′ | 84° 28 | 77° 57′ |

According to Lacroix $n_m$ has an average value of about 1.543.

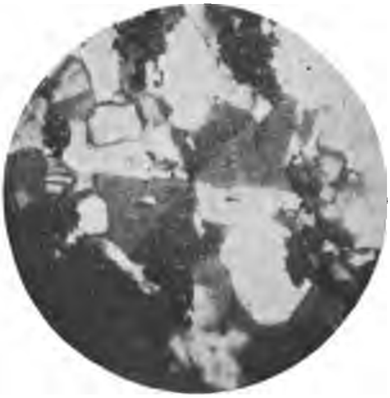


Fig. 50. Basal section of cordierite showing twinning of the type of figure 49. + nicols. × 200.

Color light to dark blue, smoky blue. Luster vitreous. Color and pleochroism are usually absent in thin sections, but when present the pleochroism is intense, as follows:—

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* A. N. Winchell. *Amer. Geol.* XXVI. p. 298, 1900.

Z = clear of various shades
Y = dark violet
X = clear yellow tinted with green or brown

Incl. Cordierite of the plutonic rocks often contains inclusions of sillimanite, spinel, staurolite, zircon, apatite and dumortierite. The last three are often surrounded by pleochroic halos which may occur even in colorless cordierite. In these halos the color parallel to X is changed to deep lemon yellow, the refringence is slightly increased, and unlike halos in other minerals, the birefringence is decreased. The halos disappear at red heat.

Cordierite of the volcanic rocks contains many vitreous inclusions of secondary origin accompanied by octahedrons of spinel, magnetite, etc. Cordierite in schists at granite contacts often contains carbonaceous inclusions regularly distributed, as in andalusite.

Alter. Cordierite alters very readily, giving rise to many products of varied aspect, which have received many names. These secondary products consist of biotite, muscovite, chlorite, and isotropic substances. Cordierite when altered chiefly to mica with development of basal lamination is called *gigantolite;* if the lamination is lacking the name *pinite* is applied. Similarly, when the alteration product is chiefly chlorite it is called *chlorophyllite* when the basal lamination is present, and *prasiolite* when it is lacking.

Occur. Cordierite is found in acid eruptive rocks, in gneiss, in schists and slates, modified by eruptive rock, especially granite, and in rock inclusions in volcanic rocks. It is usually associated with quartz, orthoclase, albite, tourmaline, andalusite, sillimanite, staurolite, spinel, garnet, zircon, etc.

Diag. Distinguished in thin section from quartz and orthoclase by inclusions (of sillimanite, staurolite, etc.), by pleochroic halos about zircon or dumortierite, and by the mode of formation of alteration products. Furthermore, the refringence of cordierite is distinctly higher than that of orthoclase, and quartz is uniaxial. Pleochroism and pleochroic halos are characteristic, if present. But perhaps the most satisfactory diagnostic is the symmetrical extinction in twins at 30° from the twinning line with both parts of the twin perpendicular to the negative acute bisectrix (basal section).

**CORUNDOPHILITE**, see chlorite group.

## CORUNDUM.

RHOMBOHEDRAL $c = 1.363$ $Al_2O_3$

PHYS. CHAR. Crystals usually hexagonal, pyramid-like forms and the base. Angles often rounded. Twinning plane the rhombohedral face $10\bar{1}1$; sometimes penetration twins, sometimes polysynthetic. Cleavages absent; but parting parallel to 0001 is sometimes perfect, though interrupted. Parting due to twinning parallel to $10\bar{1}1$ sometimes also present. H. = 9. G. = 3.95-4.10. Infusible. Insoluble in acids.

OPT. PROP. Uniaxial and negative, but often showing optic anomalies consisting of biaxial crystals or parts of crystals. The optic angle is usually small ($2E = 10°\text{-}12°$), but sometimes larger ($2E = 58°$). The biaxial character is distinct in crystals from near Bozeman, Montana. Birefringence weak; refringence high, apparently increasing in red corundum as the color becomes darker.

| | | |
|---|---|---|
| $n_g = 1.7676$ | (sapphire) | 1.7675 (ruby) |
| $n_p = 1.7594$ | (sapphire) | 1.7592 (ruby) |
| $n_g - n_p = 0.0082$ | (sapphire) | 0.0083 (ruby) |

Color blue, red, yellow, brown, gray, nearly white. Pleochroism very distinct in deeply colored varieties; ordinary gray corundum is colorless in thin section. Usually blue or gray in rocks. In thick plates,

Z = blue
X = green or bluish or colorless

ALTER. Alteration products include muscovite, spinel, cyanite, sillimanite, corundophilite, etc.

OCCUR. Usually found in crystalline metamorphic rocks such as marble, mica or chlorite slate, gneiss, etc. Also found in eruptive rocks and in rocks metamorphosed locally by eruptives. Also in stream gravels.

DIAG. Distinguished by very high relief and weak birefringence; also by its form, hardness, specific gravity, and insolubility.

**COVELLITE**, see pyrite group. **CRICHTONITE**, see ilmenite group. **CROCIDOLITE**, see amphibole group.

## CROCOITE.

MONOCLINIC $a:b:c::0.960:1:0.916$ $PbCrO_4$
$\beta = 77°\ 33'$

PHYS. CHAR. Crystals usually prismatic; various habits known. Also imperfectly columnar and granular. Cleavage good || 110, indistinct || 001 and 100. H. = 2.5-3. G. = 5.9-6.1. Fuses easily, deflagrates, and reduces to metallic lead.

Opt. Prop. The plane of the optic axes is parallel to 010; the positive acute bisectrix makes an angle with $c$ of 5½° in the obtuse angle $\beta$. Refringence extremely high. Birefringence very strong. The angle of the optic axes is large; inclined dispersion very marked with $\rho > v$ weak. Color bright red.

$$(+)\ 2V = 54°\ 3'\ (2H = 97°)$$
$$n_m = 2.42 \pm$$

Occur. Found in quartz veins in gneiss and granite with gold, pyrite, galena, vanadinite, etc. Rare.

## CRYOLITE.

Monoclinic $a:b:c::0.966:1:1.388$ $Na_3AlF_6$

$$\beta = 89°\ 49'$$

Phys. Char. Crystals commonly cubic in aspect by the development of 001 and 110 since $\beta$ is nearly 90° and $a$ and $b$ are nearly equal. Also massive, cleavable. Twinning on 110 as contact twins and also as lamellæ resembling plagioclase; twinning also on 112 in contact forms, and on $\bar{1}12$ in lamellæ, which may be produced by heat; twinning, further, on 100 in lamellæ. Cleavage perfect || 001, good || 110, distinct || $\bar{1}01$. H. = 2.5. G. = 2.95-3.0. Fusible at 2. Soluble in $H_2SO_4$ with evolution of HF.

Opt. Prop. The plane of the optic axes and the obtuse bisectrix are normal to 010; the positive acute bisectrix makes an angle of 44° with $c$ (in the acute angle $\beta$). The refringence is remarkably low, and the birefringence is weak. The angle of the optic axes is not large; axial dispersion $\rho < v$, also horizontal dispersion.

$$(+)\ 2E = 59°\ 24'$$
$$n = 1.364\text{Na}$$

Colorless to snow white; also reddish, brown, black.

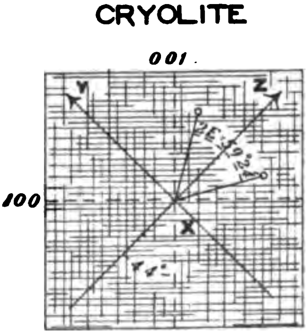


Fig. 51. Optical orientation of cryolite.

Alter. By alteration several hydrous fluorides are formed. **Pachnolite** is a monoclinic ($a:b:c::1.1626:1:1.532$; $\beta = 89°\ 40'$) hydrous fluoride of aluminum, sodium, and calcium ($NaCaAlF_6.H_2O$) commonly in long prisms with pyramidal terminations, and rare twinning on 100. The cleavage || 001 is indistinct. H. = 3. G. = 2.93-3.0. Optical orientation like cryolite, but $Z \wedge c = +68°$ and $2E = 120° \pm$; horizontal dispersion marked with $\rho < v$ weak. Optically +. Colorless to white. Only known associated with cryolite. **Thomsenolite** is also monoclinic ($a:b:c::0.9975:1:1.0329$; $\beta = 86°\ 48'$), with the same composition as pachnolite; its crystals are cubic in aspect, or prismatic: also massive, like opal. Cleavage perfect || 001, imperfect || 110. H. = 2. G. = 2.93-3.0. Fuses very easily with much decrepitation. Easily decomposed by $H_2SO_4$. Optical orientation as in cryolite, but $X \wedge c = -52°$. $2E = 69° 36'$; dispersion $\rho < v$ weak. Optically —. Colorless to white or reddish. Only known associated with cryolite. **Prosopite** is monoclinic (or triclinic) with $a:b:c::1.3188:1:0.595$ and $\beta = 85° 40'$; formula $CaAl_2(F,OH)_8$; in embedded crystals or granular massive. Crystals sometimes tabular || 010. Cleavage distinct || 211. H. = 4.5. G. = 2.88. Optic axial plane || 010; positive acute bisectrix nearly parallel to edge of pyramid 211. Refringence low, birefringence strong. Optic axial angle large; dispersion $\rho > v$ strong. $2V = 62° 45'$; $2E = 102° 50'$; $n_m = 1.502$. Colorless, white, grayish. Found with cryolite; also in veins with tin ores.

Occur. Found in large amount in a granite vein in gneiss in west Greenland associated with quartz, fluorite, siderite, cassiterite, galena, molybdenite, etc. Also known in pegmatitic quartz and microcline with zircon near Pike's Peak. Found in a topaz mine in the Ilmen Mts.

**Cryolithionite** ($Na_3Li_3Al_2F_{12}$) is a cryolite with half the sodium replaced by lithium. Isometric: cleavage || 110. H. = 2.5-3. G. = 2.73. Somewhat soluble in $H_2O$. Isotropic. Refringence very low, $n = 1.3325$Na. Colorless. Found with cryolite in Greenland. Very rare.

**CUMENGÉITE,** see percylite. **CUMMINGTONOTE,** see amphiite. **EPIDIDYMITE,** see eudidymite.

## CUPRITE.

Isometric $Cu_2O$

Phys. Char. Crystals commonly octahedrons; also cubes and dodecahedrons often much modified. Also capillary (chalcotrichite); granular, massive, earthy. Cleavage indistinct || 111. H. = 3.5-4. G. = 5.85-6.15. Fusible, giving green flame color. Soluble in pure $H_2SO_4$.

Opt. Prop. Isotropic; bright red in thin section; refringence extremely high. Color red, usually cochineal red.

$$n = 2.849.$$

Alter. Malachite is the commonest product of alteration; also native copper, azurite, or chrysocolla.

Occur. Usually in veins and confined to the upper oxidized portion. Also in cavities, or somewhat disseminated. Associated with other copper minerals.

Diag. Distinguishd from other minerals of similar color by the isotropic character.

## CUSPIDINE.

Monoclinic $a:b:c::0.724:1:1.934$ $Ca_2SiO_4$ with $CaF_2$ ?

$$\beta = 89° 22'$$

Phys. Char. Crystals minute, pyramidal, commonly twinned on 100. Cleavage distinct || 100. H. = 5.-6. G. = 2.85-2.86. Fusible with difficulty. Soluble in $HNO_3$.

Opt. Prop. The optic plane is parallel to 010; the acute bisectrix makes an angle of —5½° with $c$. $2E = 110°$ Na. Inclined dispersion very marked. Color pale rose red. Luster vitreous.

OCCUR. Found in rock fragments ejected by Vesuvius. Very rare.

**CYANITE (Disthene).**

TRICLINIC $a:b:c::0.899:1:0.697$ $Al_2SiO_5$

$\alpha = 90° 23' \ \beta = 100° 18' \ \gamma = 106° 1'$

PHYS. CHAR. Usually in long bladed crystals rarely terminated. Twinning common with 100 as the composition face and the twinning axis either perpendicular to 100, or parallel to 100 and 001, or parallel to 100 and 010. Also secondary twinning, often polysynthetic, with 001 as the twinning plane, usually accompanied by parting parallel to 001. Very perfect cleavage parallel to 100, less perfect parallel to 010. Flexible and often bent or twisted. Hardness very variable. On the cleavage face 100 the hardness is 4.-5. parallel with the vertical axis and 6.-7. parallel with 001; on the face 010 the hardness is about 7., and on $1\bar{1}0$ it is even greater. G. = 3.5-3.7. Infusible. Gives blue color with cobalt solution. Insoluble.

OPT. PROP. In the acute angle 001 ∧ 010 on the face 100 the trace of the optic plane makes an angle of about 30°.

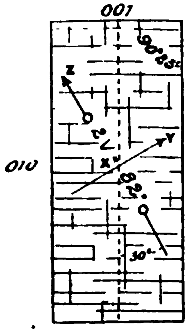


Fig. 52. Optical orientation of cyanite in a section parallel to 100.

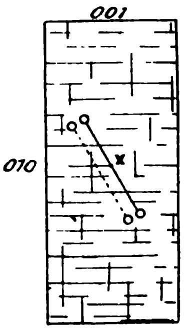


Fig. 53. Diagram parallel to 100 to show the relative position of the optic planes in twins when the twinning axis is normal to 100.

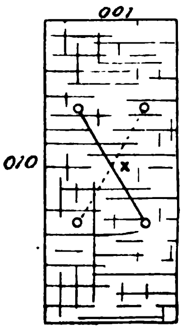


Fig. 54. Diagram parallel to 100 to show the relative position of the optic planes in twins when the twinning axis is $b$ or $c$.

The negative acute bisectrix is perpendicular to 100. The relief is very high and the optic axial angle slightly variable. The dispersion (inclined and crossed) is very weak.

$$(-)\ 2V = 82^\circ \text{ to } 84^\circ.$$
$$n_g = 1.728 \quad n_m = 1.720 \quad n_p = 1.712$$
$$n_g - n_p = 0.016$$

Color blue, white, rarely gray, green, black. Streak uncolored. Colorless in thin section; sections 0.5 mm. to 1. mm. thick often show color and pleochroism as follows:—

Z = dark cobalt blue
Y = violet blue
X = colorless

ALTER. Cyanite alters very readily to muscovite, sometimes accompanied by chlorite.

OCCUR. Found exclusively in micaschists and pegmatite veins cutting schists.

DIAG. Distinguished microscopically by numerous rectilinear cleavages, high relief, rather weak birefringence, and extinction at about 30° from the vertical axis in sections parallel to the cleavage and therefore perpendicular to the acute bisectrix. (The parting parallel to 001 makes an angle of about 90° with the vertical axis in the cleavage face).

**CYANOCHROITE**, see picromerite.

## CYANOTRICHITE (Lettsomite).

ORTHORHOMBIC Axial ratio unknown $Cu_4Al_2(OH)_{12}SO_4+2H_2O$

PHYS. CHAR. Crystals capillary, drusy; also globular. G. = 2.74.

OPT. PROP. The optic plane is parallel to the elongation and the acute bisectrix X is normal thereto. Dispersion $\rho < v$ strong. Color smalt blue to sky blue. Luster pearly. Strongly pleochroic.

OCCUR. Found with copper ores. Rare.

## DANBURITE.

ORTHORHOMBIC $a:b:c::0.544:1:0.481$ $CaB_2(SiO_4)_2$

PHYS. CHAR. Crystals usually prismatic. Cleavage in traces || 001. Irregular fractures numerous. H. = 7. G. = 2.98-3.02. Fuses readily, giving a green flame color.

OPT. PROP. The plane of the optic axes is parallel to 001; the acute negative bisectrix is perpendicular to 010 for red, yellow and green light, but on account of strong dispersion of the axes the bisectrix is positive and perpendicular to (100) for blue light. Dispersion is $\rho < v$ about X.

$$(-)\ 2V = 88^\circ 23'\text{-}88^\circ 29'\text{Na} \quad 2H = 100^\circ 20'\text{-}101^\circ 45'\text{Na}$$
$$(-)\ 2V = 87^\circ 37'\text{-}88^\circ 4'\text{Li} \quad 2H = 99^\circ\text{-}101^\circ\text{Li}$$

(—) $2V = 89° 14'$ Tl $2H = 102° 48'$ Tl
(+) $2V = 89° 4'$-$89° 36'$ $CuSO_4$ $2H = 101°$-$103°$ $CuSO_4$

| | Li | Na | Tl | $CuSO_4$ |
|---|---|---|---|---|
| $n_g =$ | 1.6331 | 1.6363 | 1.6393 | |
| $n_m =$ | 1.6303 | 1.6337 | 1.6366 | 1.646 |
| $n_p =$ | 1.6258 | 1.6317 | 1.6356 | |
| $n_g - n_p =$ | 0.0073 | 0.0046 | 0.0037 | |

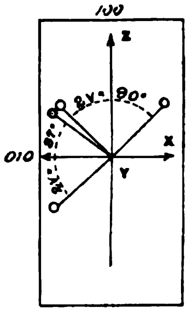


Fig. 55.
Optical orientation of danburite.

Color pale wine yellow to colorless, dark yellow, yellowish brown. Luster vitreous to greasy. Streak white.

Occur. Rare. Found in metamorphic rocks usually.

Diag. Very large optic angle, strong dispersion and weak birefringence; also fusibility with green flame, and crystal form.

### Datolite Group.

The datolite group consists of a number of basic orthosilicates of boron, aluminum, or yttrium, with calcium, iron or beryllium, which crystallize in the monoclinic system. The minerals are similar in their crystal habit, lack of good cleavage (except euclase) and some other physical characters. They usually occur in veins or cavities in crystalline rocks.

The minerals of the group are as follows:—

| | | | |
|---|---|---|---|
| Datolite | $a:b:c::0.6345:1:1.2657$ | $\beta = 89° 51'$ | $Ca(BOH)SiO_4$ |
| Homilite | $a:b:c::0.6249:1:1.2824$ | $\beta = 89° 21'$ | $Ca_2Fe(BO)_2(SiO_4)_2$ |
| Euclase | $2a:b:4c::0.6474:1:1.3330$ | $\beta = 79° 44'$ | $Be(AlOH)SiO_4$ |
| Gadolinite | $a:b:4c::0.6273:1:1.3215$ | $\beta = 89° 26\frac{1}{2}'$ | $Be_2Fe(YO)_2(SiO_4)_2$ |

## DATOLITE.

Monoclinic $a:b:c::0.6345:1:1.2657$ $Ca(BOH)SiO_4$
$\beta = 89° 51'$

Phys. Char. Usually in prismatic crystals with basal planes or in highly modified pyramidal forms. No distinct cleavage. H. = 5.-5.5. G. = 2.9-3.0. Gives water in the closed tube. Fuses readily with intumescence to a clear glass coloring the flame green. Gelatinizes with HCl.

Opt. Prop. The plane of the optic axes is parallel to 010; the negative acute bisectrix is nearly perpendicular to 100; it makes an angle of 86° to 89° in the acute angle $\beta$ with the vertical axis in crystals from different localities. The angle of the optic axes is large and the relief considerable. Weak inclined dispersion, with $\rho > v$ distinct.

(—) $2V = 75°$ to $76°$
$n_g = 1.670$ $n_m = 1.653$ $n_p = 1.626$
$n_g - n_p = 0.044$

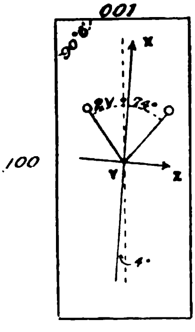


Fig. 56.
Optical orientation of datolite.

Color white, sometimes grayish, greenish, yellow, red, rarely dark green. Streak white. Colorless in thin section.

Occur. Always secondary; often associated with zeolites in basic igneous rocks; less common in acid rocks and mineral veins.

Diag. Optic properties, crystal form, presence of boron and absence of aluminum, fusibility, gelatinization.

## HOMILITE.

Monoclinic $a:b:c::0.6249:1:1.2824$ $Ca_2Fe(BO)_2(SiO_4)_2$

$\beta = 89° \ 21'$

Phys. Char. In crystals often tabular || 001 or apparently octahedral by development of 110 and 012 or 110 and $\bar{1}11$. Twins with 001 as twinning plane. Cleavage indistinct. H. = 5. G. = 3.28-3.34. Fuses readily to a black glass. Soluble in HCl with gelatinization.

Opt. Prop. The plane of the optic axes is normal to 010 and the positive acute bisectrix is nearly parallel to *c*. The angle of the optic axes is large. Dispersion distinct $\rho > v$, with very strong horizontal dispersion of the bisectrices.

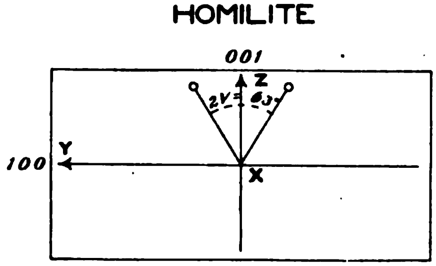


Fig. 57. Optical orientation of homilite.

$$(+) \ 2V = 80°$$
$$n = 1.678$$
$$n_g - n_p = 0.021$$

Color black or dark brown. No distinct pleochroism in thin sections. In thick sections the pleochroism is:—

Z = deep smoky gray or brownish yellow
Y = deep brownish red
X = bluish green.

Absorption visible in thick sections:— Y > X > Z.

Alter. Homilite alters easily to an amorphous isotropic substance. In many cases an exterior altered amorphous zone will enclose an unaltered birefringent center. The former is yellowish and the latter greenish in thin sections.

Occur. Found in veins in syenite in Norway. Rare.

Diag. Amorphous alteration products, high relief, no cleavage, greenish color and no pleochroism in thin section. Chemically test for boron.

## EUCLASE.

MONOCLINIC $2a:b:4c::0.6474:1:1.3330$ $Be(AlOH)SiO_4$

$\beta = 79° 44'$

PHYS. CHAR. Only found in crystals; habit prismatic, but variable on account of the multitude of planes occurring. Cleavage || 010 highly perfect; || 100 and 001 difficult. Elongated parallel to *c*. H. = 7.5. G. = 3.0-3.1. Fusible at 5.5. Insoluble.

OPT. PROP. The plane of optic axes is parallel to 010; the positive acute bisectrix makes an angle of about 41° with the vertical axis in the obtuse angle $\beta$. It therefore makes an angle of only 8° ± with the trace of $\bar{1}01$ in 010.

$(+)\ 2V = 50° \pm \quad 2E = 88°\ 40'$

$n_g = 1.671 \quad n_m = 1.655 \quad n_p = 1.652$

$n_g - n_p = 0.019$

Colorless, pale green, blue, white. Streak colorless. Colorless in thin section; sometimes distinctly pleochroic in thick plates, usually greenish, bluish, and colorless, but the orientation of the colors varies in different crystals.

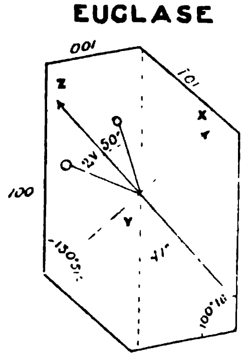


Fig. 58. Optical orientation of euclase.

OCCUR. Found in chlorite schists with topaz, etc. Rare.

DIAG. Crystal form, perfect cleavage, positive elongation with very large extinction angle, high relief and association with topaz are distinguishing characters. Also presence of beryllium.

## GADOLINITE.

MONOCLINIC $a:b:4c::0.62726:1:1.3215$ $Be_2Fe(YO)_2(SiO_4)_2$

$\beta = 89°\ 26\frac{1}{2}'$

PHYS. CHAR. Crystals rough, prismatic, terminated by the base or by acute pyramids. No cleavage. Fracture conchoidal or splintery. H. = 6.5.-7. G. = 4.-4.5. Soluble with gelatinization in HCl.

OPT. PROP. The optic plane is parallel to 010; the positive acute bisectrix Z makes an angle with *c* of 4° to 8° in the green mineral, and 12° to 13° in the brown mineral in the acute angle $\beta$. Strong dispersion with $\rho < v$. Refringence high; birefringence normally strong, but often variable even in a single crystal, and in many cases wholly absent, the crystals being amorphous.

$(+)\ 2V = 85° \quad 2H = 105°\text{-}106°$

$n_p > 1.78$

Color black, greenish black, brown. Streak greenish gray. In thin section bottle green or brownish without perceptible pleochroism.

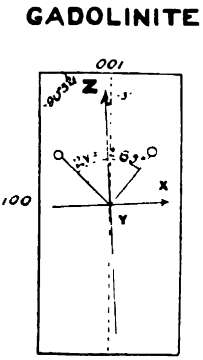


Fig. 59. Optical orientation of gadolinite.

ALTER. Alteration results in variable birefringence, and finally the amorphous state.

OCCUR. Found chiefly in pegmatite veins often associated with fluorite. Rare.

DIAG. Variable birefringence, high relief, no pleochroism in thin section, no cleavage, large optic angle, and presence of rare earths. Associated minerals aid in identifying this mineral.

### DAWSONITE.

MONOCLINIC? Axial ratio unknown $Na[Al(OH_2)]CO_3$

PHYS. CHAR. Crystals bladed, radiating; in crusts. Good longitudinal cleavage. H. = 3. G. = 2.4. Gives deep yellow flame color and swells. Effervesces with acids.

OPT. PROP. The optic plane is normal to the elongation and nearly normal to the cleavage. The birefringence is strong. Optic angle large. Color white. Luster vitreous.

OCCUR. Found as a coating resembling tremolite on joint planes of a feldspathic dike cutting limestone; also in quartzose and argillaceous rocks; commonly associated with calcite, dolomite, pyrite. Very rare.

**DELESSITE,** see chlorite group. **DESCLOIZITE,** see olivenite. **DEWEYLITE,** see serpentine group.

### DIAMOND.

ISOMETRIC C

PHYS. CHAR. Crystals commonly octahedrons, dodecahedrons; also cubes, tetrahedrons, and modified forms; faces usually curved, and often striated. Twinning on 111 common, both contact and penetration types; also on 001. Also in anhedral shapes, spherical, irregular. Sometimes radiated. Cleavage perfect || 111. H. = 10. G. = 3.2-3.52. Infusible. Insoluble in acids and alkalies.

OPT. PROP. Usually isotropic. Refringence extremely high. Sometimes shows abnormal birefringence, which may be in regular areas or localized about inclusions; rarely distinctly uniaxial. Dispersion very strong.

$$n = 2.4135 \text{Li}. \quad n = 2.4195 \text{Na}. \quad n = 2.4278 \text{Tl}.$$

Colorless, white, yellow, orange, red, green, blue, brown, black. Luster adamantine. In thin section transparent to nearly opaque, but not pleochroic.

INCL. Inclusions are gaseous or solid; often carbonaceous and abundant, thus giving color.

OCCUR. Found in alluvial deposits associated with heavy minerals; also in quartz conglomerate, in itacolumite, and in a peculiar peridotite called kimberlite. Also found in glacial drift. Also known in a few meteorites.

DIAG. The hardness, adamantine luster, and insolubility are quite distinctive. Rarely found in thin sections, even of diamondiferous rocks, because not polished by ordinary processes.

### Diaspore Group.

This is a group of hydroxides of trivalent elements. The minerals are all orthorhombic and similar in physical characters, and are to be considered isomorphous in spite of considerable variation in the axial ratios.

| | | |
|---|---|---|
| Diaspore | $a : b : c :: 0.9372 : 1 : 0.6039$ | $Al_2O_3.H_2O$ or $AlO(OH)$ |
| Goethite | $a : b : c :: 0.9185 : 1 : 0.6068$ | $Fe_2O_3.H_2O$ or $FeO(OH)$ |
| Manganite | $a : b : c :: 0.8441 : 1 : 0.5448$ | $Mn_2O_3.H_2O$ or $MnO(OH)$ |

### DIASPORE.

ORTHORHOMBIC $a : b : c :: 0.937 : 1 : 0.604$ $AlO(OH)$

PHYS. CHAR. Crystals prismatic, but usually flattened || 010. More commonly in lamellar masses. Cleavage perfect || 010, less perfect || 210. H. = 6.5-7. G. = 3.3-3.5. Insoluble in acids; soluble in sulphuric acid after calcination.

OPT. PROP. The plane of the optic axes is parallel to 010 and therefore parallel to the easy cleavage. The positive acute bisectrix is perpendicular to 100. Weak dispersion with $\rho < v$. Relief high and birefringence strong.

$$(+)\ 2V = 84° 20'$$

$$n_g = 1.750 \quad n_m = 1.722 \quad n_p = 1.702$$

$$n_g - n_p = 0.048$$

Color white, gray, greenish, brown, yellowish, colorless. Colorless in thin section; slightly pleochroic in thick sections in blue and green tints.

OCCUR. Often associated with corundum; also found in volcanic rocks with alunite; also in various schists.

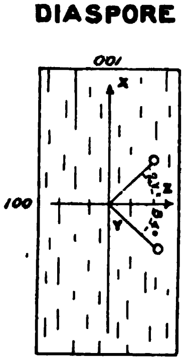


Fig. 60. Optical orientation of diaspore.

**Bauxite** is considered by Lacroix to be a rock rather than a mineral. He points out that the composition is quite variable from $Al_2O_3.3H_2O$ to $Al_2O_3.H_2O$ (at least) and that microscopical examination shows that bauxite is always colloidal. Bauxite is often composed of a mechanical mixture of colloidal aluminum hydrate with colloidal ferric hydrate and clay, and quartz sand. It often contains large amounts of silica and ferric iron, and sometimes considerable titanium oxide, phosphoric acid, etc.

Whatever the character of bauxite, it is important as a source of aluminum. There are two varieties, the white and the red. The red varieties grade into limonite iron ore of such importance that attempts have been made to use it commercially. Bauxite is found in compact or earthy masses or in concretionary masses. It is rarely absolutely white, but varies from white through gray and yellow to brown and red.

Bauxite may be distinguished from clay since it does not make a paste with water and is attacked by alkalies.

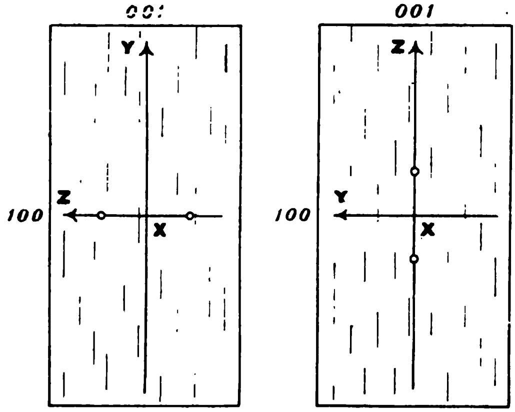
Diag. Diaspore is characterized among the lamellar minerals by the position of the optic plane parallel to the cleavage and by the strong birefringence; also by insolubility, hardness and specific gravity.

### GOETHITE.

Orth. $a:b:c::0.9185.1:0.6068$ $Fe_2O_3 \cdot H_2O$ or $FeO(OH)$

Phys. Char. In prismatic crystals vertically striated or in scales or tables flattened || 010, or more rarely || 100. Also fibrous, lamellar or compact. Perfect cleavage || 010, difficult || 100. H. = 5.-5.5. G. = 4.0-4.4. Soluble in HCl.

Opt. Prop. The optic plane is parallel to 100 for red, and parallel to 001 for yellow and green. The acute bisectrix, perpendicular to the cleavage 010, is negative for all colors. The dispersion is extremely strong $\rho < v$, recalling that of brookite, but the latter is reversed ($\rho > v$.) The elongation is positive.



Figs. 61 and 62. Optical orientation of goethite for the blue and red ends of the spectrum respectively.

| | red | yellow | green |
|---|---|---|---|
| (—) $2E =$ | $58° 31'$ | $36° 46'$ | $67° 42'$ |

$$n = 2.5 \text{ about}$$

$$n_g - n_p = 0.134$$

Color brown, yellowish, reddish. Streak yellow. In thin section the absorption is intense with $Y > X > Z$, and the pleochroic colors are:—

$Z =$ clear orange yellow
$Y =$ brownish yellow
$X =$ brown

Occur. Usually associated with hematite or limonite; also found as inclusions in quartz and feldspars.

Diag. Distinguished from limonite by presence of crystal forms, by relatively small optic angle and by its abnormally strong dispersion. Hematite is uniaxial and hexagonal. Goethite is distinguished from lepidocrocite by its abnormally strong dispersion, by its relatively small optic angle and by differing pleochroic and absorption formulas.

### MANGANITE.

Orthorhombic $a:b:c::0.8441:1:0.5448$ $Mn_2O_3.H_2O$ or $MnO(OH)$

Phys. Char. Crystals usually show many faces; striations parallel to macro-axis common. Also fibrous, lamellar, columnar or stalactitic. Twinning on 011 either of contact or penetration type. Perfect cleavage || 010 and 110. $H. = 4$. $G. = 4.2$-$4.4$. Infusible. Soluble in HCl.

Opt. Prop. Opaque except in very thin sections which are brown. Optic plane parallel to 001; the negative acute bisectrix perpendicular to the cleavage 010. Dispersion very strong, $\rho > v$. The optic angle is small. Birefringence strong.

Color steel gray to iron black. Luster submetallic. Streak dark reddish brown. In thin section pleochroism distinct in brown colors; absorption formula apparently the same as that of goethite.

Alter. Alters readily without loss of form or luster to anhydrous pyrolusite.

Occur. Found in metalliferous veins and rarely in sedimentary rocks.

Diag. Among manganese minerals manganite is distinguished by its crystal form, its easy cleavage, its frequent fibrous or lamellar state, and its streak. The color differs from that of goethite.

**DIHYDRITE**, see pseudomalachite. **DIOPSIDE**, see pyroxene group.

## DIOPTASE.

RHOMBOHEDRAL $c = 0.534$ $H_2CuSiO_4$

PHYS. CHAR. Crystals prismatic; sometimes rhombohedral; crystalline aggregates; massive. Cleavage perfect || $10\bar{1}1$. H. = 5. G. = 3.28-3.35. Infusible, but gives emerald green flame color. Gelatinizes with HCl.

OPT. PROP. Uniaxial and positive. Birefringence strong. But the mineral is frequently biaxial with rather large optic angle ($2V = 43°$ max.); the uniaxial condition and apparent rhombohedral symmetry seem to be due to submicroscopic groupings of orthorhombic individuals in which the optic plane is parallel to the shorter lateral axis and the acute bisectrix Z is normal to 001.

$$n_g = 1.697 \quad n_p = 1.644$$
$$n_p - n_p = 0.053$$

Color emerald green. Streak green. Luster vitreous. In thick sections the pleochroism is distinct with maximum absorption parallel to X.

OCCUR. Found with copper ores chiefly in veins, often with limonite and cuprite.

**DIPYRE,** see scapolite group. **DOLOMITE,** see calcite group.

## DUMORTIERITE.

ORTHORHOMBIC $a:b:c::0.4448:1:0.6871$ $H(BO)(AlO)_7Al(SiO_4)_3$

PHYS. CHAR. Usually in fibrous or columnar aggregates. Twinning with 110 as the twinning plane, often forming trillings; also interpenetrated. Cleavage distinct || 100, imperfect || 110. Parting sometimes developed || 001. H. = 7. G. = 3.26-3.36. Infusible. Insoluble even in hydrofluoric acid.

OPT. PROP. The plane of the optic axes is parallel to 010; the negative acute bisectrix is perpendicular to 001. In the twins the optic planes in contiguous individuals make angles of about 60° with each other. The angle of the optic axes has not been accurately measured. The dispersion is strong with $\rho < v$.

(—) $2V = 35°$ to $40°$ ($2E = 37°$ Na — California)

$$n_g = 1.689 \quad n_m = 1.686 \quad n_p = 1.678$$
$$n_g - n_p = 0.011$$

Color bright smalt blue to greenish blue. Luster vitreous. In thin section the pleochroism is extremely strong, as follows:—

Z = colorless or very pale blue
Y = colorless or very pale blue
X = cobalt blue or violet (or pink, or green).

The pleochroic colors parallel to X are quite variable even in a single crystal, and may be brown, red, purple or salmon pink. Unlike tourmaline the maximum absorption occurs parallel to the vertical axis (and elongation of the fibers).

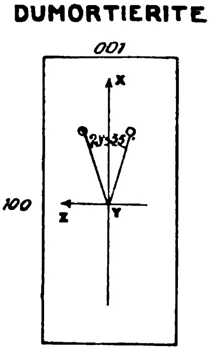


Fig. 63. Optical orientation of dumortierite.

Pleochroic halos are found about inclusions of dumortierite in cordierite.

Alter. Alters rather easily to a mica, probably muscovite.

Occur. Found only in gneiss and in pegmatite. Rare.

Diag. The intense pleochroism and also the absorption parallel to elongation, are quite characteristic. Further, the mineral is insoluble in HF.

**DURANGITE,** see amblygonite. **EDINGTONITE,** see zeolite group.

### ELPIDITE.

Orthorhombic $a:b:c::0.512:1:0.978$ $Na_2Zr(Si_2O_5)_3$

Phys. Char. Crystals prismatic; usually massive, fibrous or columnar. H. = 7. G. = 2.52-2.59.

Opt. Prop. The optic plane is parallel to 010; the acute bisectrix Z is normal to 100. Dispersion $\rho < v$ distinct. Color white to brick red.

$$(+)\ 2V = 75^\circ\ 12'\mathrm{Na}$$
$$n_g = 1.5739\mathrm{Na} \quad n_m = 1.5650\mathrm{Na} \quad n_p = 1.5600\mathrm{Na}$$
$$n_g - n_p = 0.0139\mathrm{Na}$$

Occur. Found in southern Greenland. Very rare.

**ENSTATITE,** see pyroxene group. **EOSPHORITE,** see childrenite. **EPIDIDYMITE,** see eudidymite.

### Epidote Group.

The epidote group includes a number of basic orthosilicates, one of which is orthorhombic, while the others are monoclinic. The species are:—

Orthorhombic

| | |
|---|---|
| Zoisite | $Ca_2Al_2(AlOH)(SiO_4)_3$ |

Monoclinic

| | |
|---|---|
| Fouquéite | $Ca_2Al_2(AlOH)(SiO_4)_3$ |
| Epidote | $Ca_2(Al,Fe)_2(AlOH)(SiO_4)_3$ |
| Piedmontite | $Ca_2(Al,Mn)_2(AlOH)(SiO_4)_3$ |
| Allanite | $(Ca,Fe)_2(Al,Ce,Fe)_2(AlOH)(SiO_4)_3$ |

There is undoubtedly a continuous series of isomorphous compounds from fouquéite, practically free of iron, to epidote in which the iron runs as high as seventeen or eighteen per cent ($Fe_2O_3$) corresponding to the ratio Al : Fe : : 3 : 2. Epidotes still richer in iron have not yet been found. With this increase in iron content the refringence, the birefringence, and the optic angle about Z increase, the latter being obtuse and the mineral therefore negative when the $Fe_2O_3$ exceeds about six per cent.

## ZOISITE.

ORTHORHOMBIC $a:b:c::0.620:1:0.343$ $Ca_2Al_2(AlOH)(SiO_4)_3$

PHYS. CHAR. Crystals usually prismatic, deeply striated vertically. Also in lamellar, fibrous or compact masses. Cleavage perfect parallel to 010, very difficult parallel to 100. Microscopic twinning common, sometimes in polysynthetic bands like plagioclase; it is claimed by some writers that the variations in optical characters are to be explained by this twinning, and that the mineral is probably monoclinic. H. = 6. G. = 3.25-3.36. Fusible with swelling at about 3. Insoluble.

OPT. PROP. The positive acute bisectrix is perpendicular to 100, the optic plane is parallel to 010. The angle of the optic axes is variable even in a single crystal; it increases rapidly with increase in temperature. The dispersion is very strong with $\rho < v$.

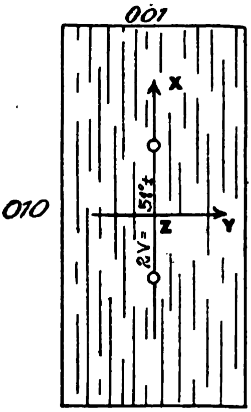


Fig. 64. Optical orientation of α-zoisite.

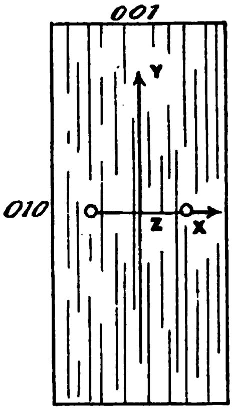


Fig. 65. Optical orientation of β-zoisite.

$$(+)\ 2V = 51^\circ \text{ about}$$

$$n_g = 1.702 \quad n_m = 1.699 \quad n_p = 1.697$$

$$n_g - n_p = 0.005$$

Color gray, greenish, brown, green. Streak colorless. In thin section colorless. The pink manganiferous variety, *thulite,* has strong pleochroism in thin section as follows:—

Z = yellow
Y = bright pink
X = dark pink

OCCUR. Found in crystalline schists and as a secondary product in many igneous rocks. In schists usually associated with some variety of amphibole. In igneous rocks zoisite is commonly the result of alteration of basic feldspars. Thus, *saussurite* is merely a name given to a feldspar mass more or less completely altered to a mixture of zoisite, new feldspars, actinolite, chlorite, etc. Also found in veins in altered basic igneous rocks with quartz.

**β-Zoisite.** In addition to the common zoisite described above, and distinguished as **α-zoisite** there is another type (dimorphous?) called β-zoisite in which the plane of the optic axes is parallel to the base 001 and the acute positive bisectrix is perpendicular to 100. Moreover the dispersion is weak and variable with $\rho > v$. The indices of refraction and the birefringence are about the same as in common zoisite, but the angle of the optic axes is considerably smaller. α-zoisite and β-zoisite, as well as epidote, often occur together, sometimes intimately intergrown.

DIAG. Distinguished in thin section by elongated sections with parallel extinction, high relief, very weak birefringence, and very strong dispersion. On account of the last character complete extinction is not obtainable, but instead one has the "ultra blue," also seen with chlorite. The elongation is of variable sign when the optic plane is parallel to 010 and negative when it is parallel to 010. Differs from epidote in absence of color and much weaker birefringence.

## FOUQUÉITE.

MONOCLINIC $Ca_2Al_2(AlOH)(SiO_4)_3$

PHYS. CHAR. Similar to epidote in form and physical characters; similar to zoisite in composition. It has a cleavage (parallel to 001?) making an angle of at least 108° with the elongation of the crystals. Sometimes occurs in polysynthetic twins, with 100 as the composition plane. G. = 3.3. Infusible.

OPT. PROP. The plane of the optic axes is probably parallel to 010*. There is a continuous variation in the refringence, birefringence, and optic angle with varying $Fe_2O_3$, as follows:—

| LOCALITY | $Fe_2O_3$ | $n_g$ | $n_m$ | $n_p$ | $n_g - n_p$ | $2V$ | SIGN |
|---|---|---|---|---|---|---|---|
| Ceylon | (FeO?=4.4) | | | | 0.020 | near 90° | + |
| Inverness-shire | 6.8 | 1.725Na | 1.7196 | 1.714 | 0.011 | 89° 31′ Tl | + |
| Rothenkopf | 4. | 1.7343 | 1.7291 | 1.7138 | 0.0105 | 89° 16′ | + |
| Prägraten<br>(Clinozoisite-see below) | 2 | 1.7232 | 1.7195 | 1.7176 | 0.0056 | 81° 40′ | + |

Color gray, greenish, rarely colorless. Streak colorless. Colorless, or nearly so, in thin section; colored varieties have very weak pleochroism, as follows:

---

* In the original description (*Bull. Soo. Fr. Min.* XII, 327.) Lacroix states that the optic plane is parallel to the easy cleavage, which he takes for the base, but this is inconsistent with his description of extinction and cleavage in the twins.

Z = colorless
Y = very pale yellow
X = colorless

Occur. Found in anorthite gneiss. Rare.

Diag. Differs from epidote in sign, absence of color and pleochroism, and weaker birefringence. Differs from zoisite in inclined extinction and larger optic angle.

**Clinozoisite** seems to be a synonym of fouquéite. It has the same composition and similar physical characters. G. = 3.35-3.37. H. = 7. The plane of the optic axes is parallel to 010. The positive acute bisectrix makes an angle of 2° with the crystal axis *c*. The angle of the optic axes is very large. The dispersion is very strong, with $\rho > v$. $2V = 18° 40'$; $n_g = 1.7232$, $n_m = 1.7195$, $n_p = 1.7176$; $n_g - n_p = 0.0056$. Rare.

## EPIDOTE.

Mono. $a:b:c :: 1.586 : 1 : 1.815$ $Ca_2(Al,Fe)_2(AlOH)(SiO_4)_3$
$\beta = 64° 33'$

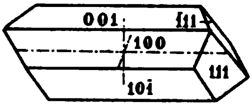


Fig. 66. Common crystal form of epidote.

Phys. Char. Crystals nearly always elongated || the axis *b*; faces in this zone usually striated || *b*. Also fibrous, granular and massive. Twinning often polysynthetic || 100. Cleavage very good || 001, imperfect || 100. H. = 6.-7. G. = 3.3-3.5. Fusible with intumescence at about 3. Partly decomposed by HCl.

Opt. Prop. The plane of the optic axes is parallel to 010. The acute negative bisectrix makes a very small angle with the vertical axis in the acute angle $\beta$. The values of the indices of refraction and of the angle of the optic axes are very variable, sometimes even in a single crystal. These variations are apparently dependent upon the percentage of $Fe_2O_3$, as shown in the table below. Inclined dispersion; also dispersion $\rho > v$.

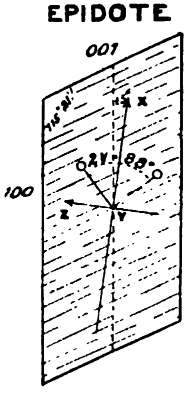


Fig. 66a. Optical orientation of epidote.

| Locality | $Fe_2O_3$ | $n_g$ | $n_m$ | $n_p$ | $n_g - n_p$ | $2V$ | Sign |
|---|---|---|---|---|---|---|---|
| Zillerthal | 7.9 | 1.7344 | ...... | 1.720 | 0.0144 | 87° 46′ | — |
| Knappenwand | 16. | 1.7677 | 1.7540 | 1.7305 | 0.0372 | 73° 39′ | — |
| Cabre | .. | ...... | ...... | ...... | 0.016-0.054 | ...... | — |
| Traversella | .. | ...... | ...... | ...... | 0.061 | ...... | — |

Color green of various shades, sometimes yellow, gray or nearly colorless. In thin section usually colorless to orange yellow, the pleochroism increasing with the amount of color. The absorption formula is $Y > Z > X$.

| | Sections 0.03 mm. | Sections thick. |
|---|---|---|
| Z = | colorless, yellowish green, pink | yellow |
| Y = | pale blue to greenish yellow | brown |
| X = | colorless, lemon yellow, pale green | green |

Occur. Epidote is a very common mineral, occurring in great abundance in schists and in contact zones. It is also common as an alteration product of ferromagnesian minerals and feldspars, etc.

*Withamite* is a variety containing a little MnO and characterized by red color; the birefringence is about 0.05 and the pleochroic colors are Z = bright rose, Y = light rose; X = lemon yellow.

Diag. The high refringence, parallel extinction in longitudinal sections, and inclined extinction in transverse sections, and the strong birefringence variable in a single crystal, are quite characteristic. The forms and color are also good diagnostics.

## PIEDMONTITE.

Monoclinic $a : b : c :: 1.610 : 1 : 1.833$ $Ca_2(Al,Mn)_2(AlOH)(SiO_4)_3$

$\beta = 64° 39'$

Phys. Char. Similar to epidote in physical characters. G. = 3.4. H. = 6.5.

Opt. Prop. The plane of the optic axes is parallel to 010; the positive acute bisectrix makes an angle of 32° with the trace of 001. The maximum birefringence is about the same as that of epidote; the refringence is also similar.

$$(+) \; 2V = 79° \pm$$

$$n = 1.73$$

$$n_g - n_p = 0.05 \pm$$

Color reddish brown, reddish black. Streak reddish. The pleochroism is characteristic and intense even in thin section. The absorption formula is $X > Y > Z$.

Z = bright red
Y = amethyst violet
X = lemon to orange yellow

Occur. Common in crystalline schists in some parts of Japan; not uncommon as an accessory in glaucophane schist and Archean gneiss, etc.

Diag. Very similar in general to epidote, from which it is distinguished by its color, pleochroism, positive bisectrix, and by manganese reactions.

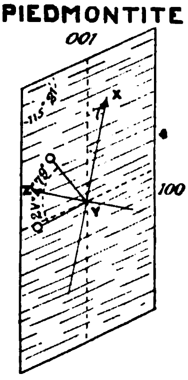


Fig. 67. Optical orientation of piedmontite.

## ALLANITE (Orthite).

MONO. $a:b:c::1.551:1:1.768$ $(Ca,Fe)_2(Al,Ce,Fe)_2(AlOH)(SiO_4)_3$
$\beta = 64° 59'$

PHYS. CHAR. Similar to epidote in physical characters; cleavages often indistinct. H. = 6. G. = 3.-4.

OPT. PROP. The plane of optic axes is parallel to 010; the negative acute bisectrix makes a very small angle with the vertical axis in the acute angle $\beta$. The optic axes are respectively sensibly perpendicular to 001 and $\bar{1}01$. The dispersion is very strong rendering extinction incomplete. The birefringence is quite variable, often even in a single crystal; this variation often seems to be in relation with colored zones. In some cases the mineral is wholly or in large part isotropic. In such cases pleochroism is absent.

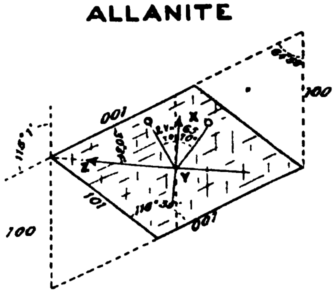


Fig. 68. Optical orientation of allanite.

$(-)\ 2V = 65°$ to $70°$

$n_m = 1.68\text{-}1.70$

$n_g - n_p = 0.032$ (maximum)

Color brown to black with tints of green, gray or yellow. Streak gray. In thin section the pleochroism is usually very marked as follows:—

| | |
|---|---|
| Z = yellowish brown | reddish brown |
| Y = dark reddish brown | reddish brown |
| X = pale greenish brown | yellowish brown |

Allanite often produces intense pleochroic halos in biotite. It is not rare to find allanite surrounded by a zone of epidote having the same orientation, but slightly different extinction.

OCCUR. Rather common as an accessory constituent of many igneous rocks, especially the more acid varieties. Also in gneiss, crystalline schists, and magnetite iron mines.

DIAG. The high refringence, varying color (even in a single crystal), pleochroism in brown tints, great variations in birefringence and association with epidote are distinguishing characteristics.

**EPISTILBITE**, see zeolite group.

## EPSOMITE.

ORTHORHOMBIC $a:b:c::0.9902:1:0.5709$ $MgSO_4 + 7H_2O$

PHYS. CHAR. Crystals prismatic in habit, often hemihedral. Also in fibrous crusts and fibrous botryoidal masses. Cleavages perfect || 010, imperfect || 011, in traces || 110. H. = 2.-2.5. G. = 1.75. Liquifies in its water of crystallization. Has very bitter taste.

OPT. PROP. The plane of the optic axes is parallel to 001; the negative acute bisectrix is normal to 010. The refringence is very low, the birefringence rather strong. The angle of the optic axes is rather large; dispersion weak $\rho > v$.

$$(-)\ 2V = 51^\circ\ 25'\ (2E = 78^\circ\ 18')$$
$$n_g = 1.4608 \quad n_m = 1.4554 \quad n_p = 1.4325$$
$$n_g - n_p = 0.028$$

Color white. Colorless in section.

Occur. Found in capillary coatings on the walls and floors of caves and mine galleries; also in the gypsum quarries of Paris; in anthracite; in thin layers with carnallite at Strassfurt, etc.

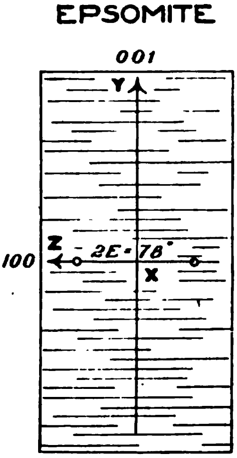


Fig. 69. Optical orientation of epsomite.

**Goslarite** ($ZnSO_4 + 7H_2O$) is related to epsomite both in composition and form being orthorhombic and having $a : b : c :: 0.981 : 1 : 0.563$. It is commonly in acicular to fibrous crystals, in tufts, stalactitic, or massive. Cleavage perfect || 010. H. = 2.-2.5. G. = 1.9-2.1. Soluble in $H_2O$; taste astringent. Optic orientation as in epsomite, but the optic angle about X is larger, $2E = 70^\circ\ 23'$ Li ($2V = 46^\circ\ 14'$ Na) and the dispersion is very weak $\rho < v$. The refringnce is very low; $n_g = 1.4836$, $n_m = 1.4801$, $n_p = 1.4568$; $n_g - n_p = 0.027$. Color white or stained. Found in passages of mines precipitated from solution in stalactitic forms, etc.

**Morenosite** ($NiSO_4 + 7H_2O$) is isomorphous with epsomite, having $a : b : c :: 0.982 : 1 : 0.566$. Commonly acicular to fibrous. Cleavage perfect || 010. H. = 2.-2.5. G. = 2. Soluble in $H_2O$; taste astringent. Optic orientation as in epsomite. $2E = 64^\circ\ 22'$ Na ($2V = 41^\circ\ 56'$); dispersion distinct $\rho > v$. Refringence low, $n_g = 1.4921$, $n_m = 1.4888$. $n_p = 1.4669$; $n_g - n_p = 0.025$. Optic sign —. Color apple-green to greenish white. Occurs as an efflorescence on nickel sulphide ores.

**ERYTHRITE,** see vivianite.

## EUCHROITE.

Orthorhombic $a : b : c :: 0.609 : 1 : 1.038$ $Cu_2(OH)AsO_4 + 3H_2O$

Phys. Char. Crystals prismatic, vertically striated. Cleavage in traces || 110 and 011. H. = 3.5-4. G. = 3.39. Easily fusible with bluish green flame color. Soluble in $HNO_3$.

Opt. Prop. The optic plane is parallel to 100; the acute bisectrix Z is normal to 001. Refringence high, $n = 1.70$. $2E = 61^\circ\ 11'$. Color bright emerald green, leek green. Luster vitreous.

Occur. Found in slate; resembles dioptase. Very rare.

**EUCLASE,** see datolite group. **EUCRYPTITE,** see nephelite group.

### EUDIALYTE (Eucolite).

Hexagonal $c = 2.112$ $Na_{18}(Ca,Fe)_6Cl(Si,Zr)_{20}O_{52}$

Phys. Char. Crystals of varied habits. Cleavage distinct || 0001, indistinct || $11\bar{2}0$. H. = 5.-6. G. = 2.9-3.1. Fusible at 2.5, Gelatinizes with HCl.

Opt. Prop. Uniaxial and positive (eudialyte) or negative (eucolite). Pale pink in thin section without perceptible pleochroism.

| | *Eudialyte* | *Eucolite.* |
|---|---|---|
| $n_g =$ | 1.610Na to 1.613 | 1.6205 to 1.622 |
| $n_p =$ | 1.608 to 1.604 | 1.6178 to 1.618 |
| $n_g - n_p =$ | 0.002 to 0.009 | 0.0027 to 0.004 |

Ramsay considers that eudialyte and eucolite form an isomorphous series between the end members (with maximum positive and maximum negative birefringence) of which there are mixtures, some positive, some negative and some isotropic, at least for certain colors.

Occur. Associated with sodalite, nepheline, acmite and other soda minerals in Greenland, Norway and Arkansas. Rare.

Diag. Uniaxial character, rather high relief, weak birefringence and association with soda minerals are distinguishing characters.

### EUDIDYMITE.

Monoclinic $a : b : c :: 1.7107 : 1 : 1.107$ $HNaBeSi_3O_8$

$\beta = 86° \ 14\frac{1}{2}'$

Phys. Char. Crystals tabular || 001, always twinned on 001 in thin lamellæ; also interpenetrated; also contact twins with reëntrant angles near 120°. Cleavage perfect || 001, imperfect || $\bar{5}51$. H. = 6. G. = 2.55. Fusible easily. Incompletely soluble in acids.

Opt. Prop. The plane of the optic axes is parallel to 010; the positive acute bisectrix makes an angle with *c* of 58° in the acute angle *β*. The refringence is low and the birefringence weak. The angle of the optic axes is small; dispersion distinct, $\rho > v$.

$$(+) \ 2V = 29° \ 19'$$

$$n_g = 1.55085\text{Na} \quad n_m = 1.54568\text{Na} \quad n_p = 1.54533\text{Na}$$

$$n_g - n_p = 0.0055$$

Color white. Colorless in section.

Occur. Found in cavities in zircon syenite associated with natrolite, apophyllite, nepheline, etc. Very rare.

**Epididymite** has the same composition as eudidymite, but is orthorhombic with $a : b : c :: 0.576 : 1 : 0.534$. Crystals often tabular || 001, either hexagonal in outline or elongated || *a*. Twinning on 001 with revolution of 60°. Cleavage perfect || 001 and 010. H. = 5.5. G. = 3.55. Fusible easily; insoluble. The optic axial plane is parallel to 001; the acute negative bisectrix is normal to 010. Dispersion $\rho \gtrless v$. $2V = 22° \ 38'$ Na; $n_g = 1.5464$ Na, $n_m = 1.5441$, $n_p = 1.5440$; $n_g - n_p = 0.0064$ Na. Colorless. Very rare.

**FAYALITE,** see olivine group.

**Feldspar Group.**

The feldspars constitute a group with many common characters. They are silicates of aluminum with potassium, sodium, or calcium (rarely barium). Their crystal forms are similar although some are monoclinic and others triclinic. They all possess two good cleavages making an angle of 90° in the monoclinic feldspars and 90°+ to 94° 10′ in the triclinic feldspars. These cleavages are parallel to the base 001 and to the pinacoid 010; the basal cleavage is distinct and easily obtained, the pinacoidal cleavage slightly less distinct. Cleavage parallel to some other faces is found in some feldspars, but only in traces. The specific gravity of the feldspars ranges from 2.5 to 2.9 and the hardness from 6. to 6.5. They are naturally glassy and colorless, but are often clouded and stained by impurities of various kinds.

Crystal form. The similarity of crystal form of all the feldspars, both monoclinic and triclinic is shown in the following table; here, and in other tables which follow, the composition is often expressed in terms of the celsian molecule ($BaAl_2Si_2O_8 = Cn$), the orthoclase molecule ($KAlSi_3O_8 = Or$), the albite molecule ($NaAlSi_3O_8 = Ab$), and the anorthite molecule ($CaAl_2Si_2O_8 = An$).

*Crystallography of the feldspars.*

| Name | *a*:*b*:*c* | α | β | γ | 001∧010 | Approx. Comp. |
|---|---|---|---|---|---|---|
| Celsian | 0.657:1:0.554 | 90° | 115° 2′ | 90° | 90° | Cn |
| Hyalophane | 0.6584:1:0.5512 | 90° | 115° 35′ | 90° | 90° | (Or,Cn) |
| Orthoclase | 0.6586:1:0.5559 | 90° | 116° 3′ | 90° | 90° | Or |
| Microcline | 0.6495:1:0.5546 | 90° 7′ | 115° 50′ | 89° 55′ | 89° 53′ | Or |
| Anorthoclase | 0.6466:1:0.5522 | 90° 30′ | 116° 18′ | 90° ± | 90° ± | (Ab,Or) |
| Albite | 0.6331:1:0.5572 | 94° 3′ | 116° 27′ | 88° 9′ | 93° 36′ | Ab |
| Oligoclase | 0.6321:1:0.5524 | 93° 4′ | 116° 22′ | 90° 4′ | 93° 28′ | $(Ab_4An_1)$ |
| Andesine | 0.6356:1:0.5521 | 93° 23′ | 116° 29′ | 89° 59′ | 93° 46′ | $(Ab_3An_2)$ |
| Labradorite[1] | 0.6377:1:0.5547 | 93° 31′ | 116° 3′ | 89° 54′ | 93° 52′ | $(Ab_1An_1)$ |
| Anorthite | 0.6342:1:0.5501 | 93° 13′ | 115° 57′ | 91° 13′ | 94° 10′ | An |

Feldspar crystals are often short prismatic in habit, somewhat flattened parallel to 010, as in figures 70, 71, and 71a; they are also frequently elongated in the plane of symmetry, that

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[1] The crystallographic study of labradorite has not yet been completed satisfactorily. The figures given above are chiefly those of Obermeyer.

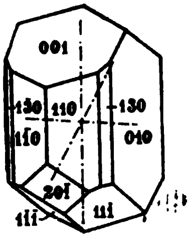

Fig. 70.

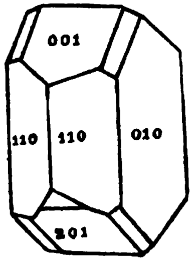

Fig. 71.

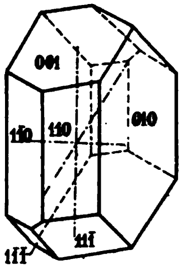

Fig. 71a.

Simple crystal forms of feldspars.

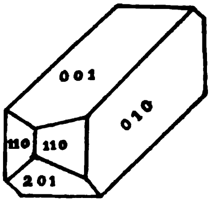

Fig. 72.

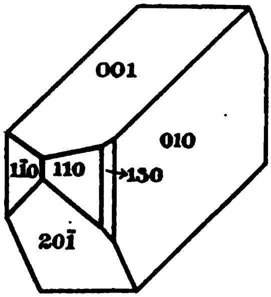

Fig. 73.

Simple crystal forms of feldspars.

is parallel to the face 010, in the direction of the horizontal axis, (*a*), the crystals then taking the forms of quadratic prisms, the real prism faces 110 and $1\bar{1}0$ being reduced to comparatively insignificant dimensions, as in figures 72 and 73. Feldspar microlites are usually in thin lamellæ parallel to 010, as in figures 74 and 75.

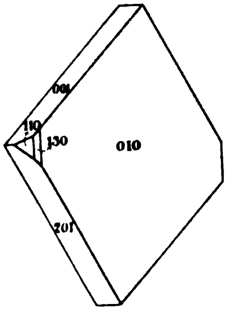

Fig. 74.

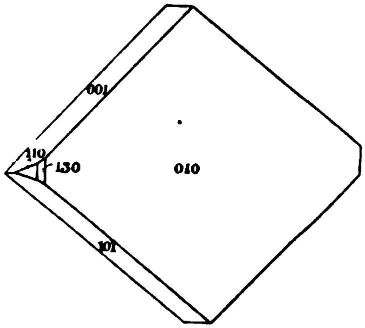

Fig. 75.

Crystal forms of microlitic feldspars.

Anorthoclase is often elongated parallel to the vertical axis.

The plagioclase feldspars are distinctly triclinic, yet the angle *a* varies very little from 90°, and their forms are therefore quite near those of the monoclinic species. The plagioclase feldspars are sometimes elongated parallel to the axis *b*; this elongation produces the pericline variety of albite, and when twinned gives rise to the pericline striations which may appear in any plagioclase on 100 and 010.

TWINNING. The feldspars are all subject to twinning. Orthoclase is especially frequent in the form of Carlsbad twins, but also shows the Manebach (Four-la-Brouque) and Baveno types.

In the Carlsbad form the twins are united by some plane, usually 010, parallel to the vertical axis. One is turned 180° from the position of the other about the common vertical axis. The Carlsbad twins may be united in a single plane as in figure 76, or partially interpenetrate as in figure 77. In a thin section of a Carlsbad twin the pinacoidal cleavage 010 in one twin is parallel with that in the other, and unless the section be cut in a zone whose axis is either parallel or perpendicular to the face 010, the basal cleavages form oblique angles with one another. If a section be in a zone whose axis is either parallel or perpendicular to the face 010 the cleavages will stand at right angles. Carlsbad twins are almost invariably composed of only two individuals. This is a fact of considerable importance in distinguishing macroscopically, and also in a cursory way microscopically, between orthoclase and plagioclase. Twinning of the polysynthetic type is almost always present in the latter.

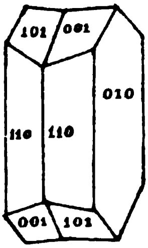

Fig. 76.
Carlsbad contact twin.

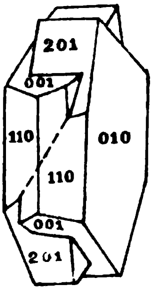

Fig. 77.
Carlsbad partial penetration twin.

The Manebach type (figure 78), has the basal plane as composition face, and the axis about which the crystal turns is the vertical crystallographic axis. The cleavages 001, of one twin, are parallel to those of 001 of the other. The same is true of the cleavages 010.

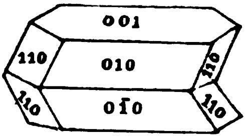

Fig. 78. Manebach twin.

In Baveno twinning the twinning axis is perpendicular to 021 which is the composition face. Crystals twinned according to this law are always elongated parallel to the axis *a* and often flattened parallel to 001. Twins of this kind form nearly square prisms as seen in figure 79 since 001∧021 is nearly 45°, being 44° 56′ in orthoclase and 46° 46′ in albite. Sections cutting such a twinned crystal present square or rhombic outlines, the cleavages being parallel to the sides. The line separating the twins runs diagonally from corner to corner, as seen in figures 80 and 81.

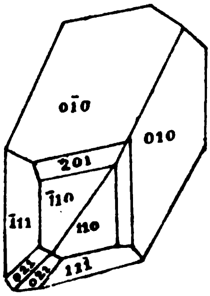

Fig. 79.
Baveno twin.

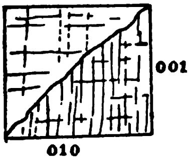

Fig. 80.

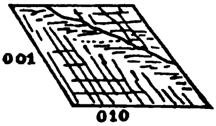

Fig. 81.

Baveno twins in thin sections; perpendicular section and oblique section.

The twinning of anorthoclase and microcline is characteristic. They combine the albite and pericline types, producing a rectangular quadrillage on all sections of the zone 001 : 100, except on that which is parallel to the plane of association for the pericline law, and on all sections in the zone 001 : 010 except on that parallel to the composition face of the albite law. In other words, the section parallel to 010 is identified by the disappearance of the albite twinning and that parallel to the composition face of the pericline twinning by the disappearance of the pericline marks. The position of the composition face of the pericline twinning in anorthoclase coincides with its position in oligoclase in some cases; in other cases it seems to make an angle of —78° to —75° with 001 in 010. In both cases it is practically perpendicular to the face 010. In microcline this plane, while nearly perpendicular to 001, and practically perpendicular to 010, has a trace on 010 which forms an angle of —80° or + 100° with the edge 001 : 010 (figure 87). Its position is between the faces 100 and 201. The cross-hatching of microcline is represented by figure 82. That of anorthoclase is less distinct, being extremely fine and badly defined. But anorthoclase with only one type of twinning present is not rare.

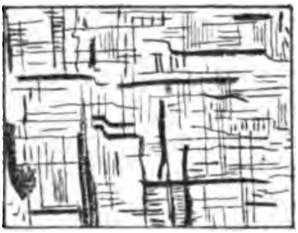

Fig. 82. Quadrillage of microcline. See also figure 104.

With the plagioclases, properly so called, the albite and pericline types of twinning play an important rôle. In albite twinning the composition face and the twinning plane are both 010. Simple albite twins are represented in figures 83, 84 and 85. This is the twinning characteristic of the plagioclase feldspars in which it is rarely lacking. It is nearly always polysynthetic, producing striations on the cleavage face 001 parallel to the face 010. This twinning becomes a case of parallel growth and is therefore optically invisible in orthoclase, since the latter is monoclinic and the twinning axis is consequently an axis of binary symmetry.

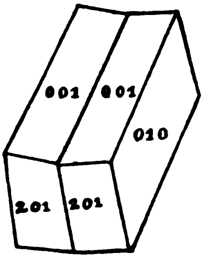

Fig. 83.

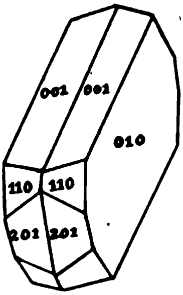

Fig. 84.

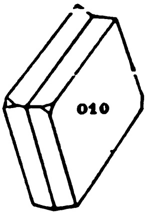

Fig. 85.

Simple albite twins.

In pericline twinning the twinning axis is the axis *b*, while the composition face is the so-called rhombic section, which is a section made by a plane passing through the crystal in such a direction that its intersections with the prism faces 110 and 1$\bar{1}$0 and the brachypinacoid 010 make equal plane angles with each other, (see figure 86). The position of this rhombic section and the consequent direction of the twinning bands on 010 change rapidly with small changes in the crystallographic axial angles. The pericline twinning bands, when visible in a section parallel to 010, make different angles with the basal cleavages which are visible in the same section, according to the feldspar examined. This angle varies from 0° for andesine to —18° for anorthite, in one direction, and in the other direction it varies to + 13° and + 21° for albite. It may be represented for all the triclinic feldspars by the diagram below (figure 87), which shows the face

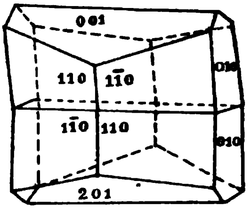

Fig. 86. Simple pericline twins.

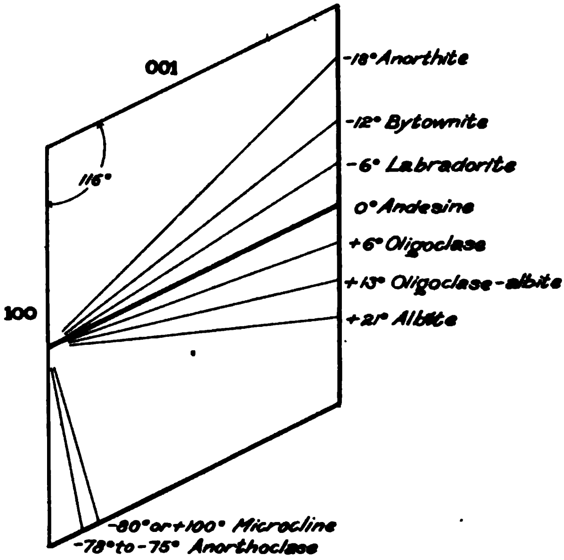

Fig. 87. Position of composition face of pericline twinning in the triclinic feldspars.

010 of a simple crystal. In microcline, and apparently in anorthoclase, this type of twinning exists with a composition face which is not a "rhombic section." Except rarely in the species

albite, pericline twinning is polysynthetic, and always invisible without the microscope.

The Ala twinning is simple, and resembles the Carlsbad. Its composition face is 001, and the twinning axis is the axis *a*. In oligoclase and andesine this type of twinning retains the axis Z in coincidence with its primitive direction.

The plagioclases are subject to twinning on the Carlsbad, Manebach, and Baveno plans, and albite also on the Roc Tourné plan. This last consists of two albite twins, again twinned as couples by the union of the reëntrant angle formed by the faces $\bar{1}01$, 101, of one upon the salient angle of the other formed by the same faces. The double crystal thus formed is approximately a parallelogram, flattened parallel to 010, one of the twinned pairs being thinner than the other as shown by figure 88.

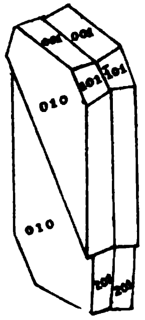

Fig. 88.
Roc tourné twin of albite.

In thin section the twinning lines of albite are fine and far apart, often irregular and interrupted: those of oligoclase are very clear and of very regular widths, one of the systems being much more fine than the other,—so fine indeed that sometimes it is impossible to perceive the width. In labradorite the lamellæ are equally clear and definite, but the width varies much from one lamella to the other, and in the same lamella (rarely) from one point to another. In anorthite the albite lamellæ are broad and regular, while those of pericline are very frequently distributed only in certain ones of the albite bands, which they cross at varying angles according to the direction of the plate.

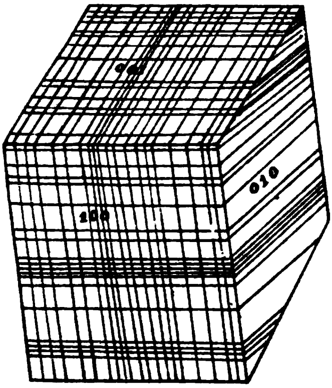

Fig. 89.
External albite and pericline striations.

Figure 89 represents a triclinic feldspar crystal with the albite and pericline striations, much amplified to show their positions and direction for the species albite. The front face, 100, is represented, but it is very rarely seen in nature. The prism planes, 110, $1\bar{1}0$, obliterate it.

As a brief summary statement of twinning in the feldspars it may be said that orthoclase often occurs in simple twins, but never in polysynthetic twins; microcline is always polysynthetically twinned in two directions giving a fine cross hatching between crossed nicols; plagioclase is nearly always polysynthetically twinned on the albite law.

Optical Properties. In the study of the feldspars it is frequently necessary to indicate the position of a right line situated in the plane 001 or in 010. In order that such designation may be free from ambiguity it has been suggested by Schuster that the direction of such line shall be uniformly referred to the edge 001 : 010 with the crystal in the conventional position, whether in the plane 001 or in 010. The angle in the brachypinacoid which the line makes with this edge is called *positive* if the direction of the line is included in the obtuse angle formed by the edges 001 : 010, 010 : 100, and *negative* if its direction lie in the acute angle of these same edges. The same rule is applied for a line lying in the base 001. Figure 90 represents a simple plagioclase crystal with lines drawn in the faces 001 and 010 with their directions expressed according to Schuster.

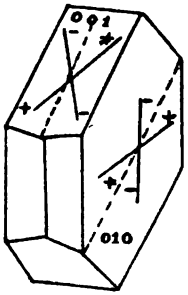

**Fig. 90.**
**Sign of extinction angles in feldspars.**

The principal optic element is the optic plane (p. 71). In it lie the optic axes and the bisectrices. Its position in the crystal has definite relations to the cleavages, the external faces, and the crystallographic axes in the different feldspars, and its angle with the albite twinning, in the plagioclases, is the key which furnishes one of the principal diagnostics. Its position is best expressed, summarily, by projections on the plane perpendicular to the edge 001 : 010. Figure 91 shows the comparative positions of the optic plane in orthoclase, anorthoclase and microcline, as given by Michel Lévy and Lacroix*. It appears that in these potash feldspars the axial plane is nearly parallel to the base 001, and consequently agrees substantially with the direction of the easy cleavage. It appears also that the least axis of ether vibration (Z) is nearly or quite perpendicular to the face 010. The greatest axis of ether vibration (X) lies in the plane 010 and nearly parallel to the base, varying in microcline 5° into the

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* *Minéraux des Roches*, p. 192.

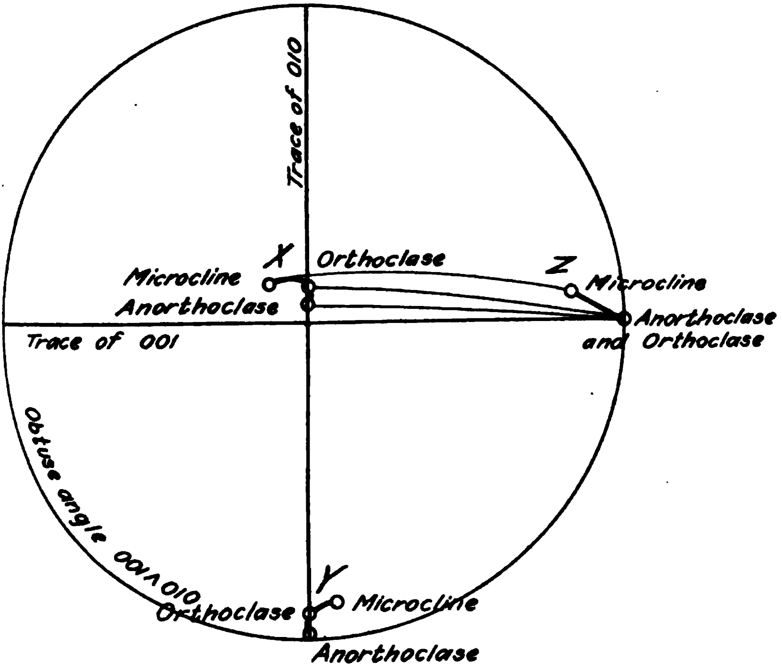

Fig. 91. Stereographic projection of the axes X, Y, Z in orthoclase, microcline, anorthoclase on a plane normal to the axis *a*.

acute angle, and the mean axis of ether vibration (Y) is perpendicular to 001 except in microcline in which it varies from 3° to 5° from perpendicularity.

In a few sanidines (a glassy form of orthoclase), the axial plane is perpendicular to the easy cleavage, in which case the axes Z and Y mutually change places. Such orthoclase is distinguished by Michel Lévy as *orthose déformé* or abnormal orthoclase.

In the soda-lime feldspars the position of the optic plane is more varied. It is represented in figure 92 as projected on a plane perpendicular to the edge 001 : 010, the bisectrix X being perpendicular or at least less inclined to the surface of projection than Y, and Z lying approximately in the paper. From this it appears that from albite to anorthite there is a gradual rotation of the optic plane in a direction opposite to the movement of the hands of a watch about a line parallel (or nearly parallel) to X, and that the whole movement amounts to somewhat less than one-fourth of an entire revolution.

It is represented in figure 93 as projected on the face 010. From this it appears that the projection of the optic plane

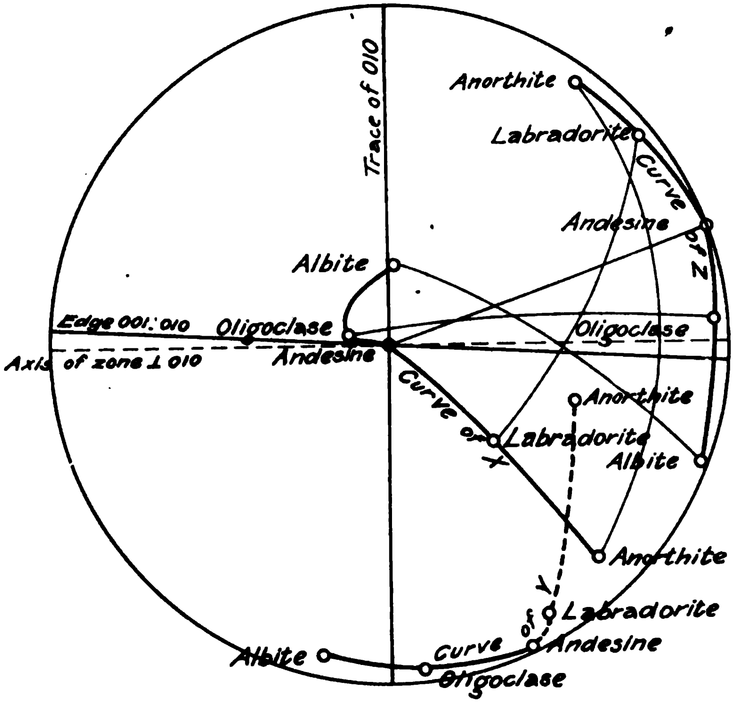

Fig. 92. Stereographic projection of the axes X, Y, Z in the plagioclase feldspars on a plane normal to the axis *a*.

rotates in a similar manner, from this point of view about a line nearly parallel to Z.

The least axis of ether vibration Z of all the plagioclases is situated nearly in the plane perpendicular to the edge 001 : 010. while the greatest axis of ether vibration X is nearly parallel to that edge, and in the brachypinacoid 010.

*Refringence and Birefringence.* The feldspars all possess low refringence and weak birefringence, both being about the same as for quartz. By these characters, therefore, it is sometimes difficult to distinguish them, when pure, from quartz. When other diagnostics are not available resort may be had to the Becke method of distinction* of comparative refringence. This consists in the following very delicate process:

In convergent light, with a high power (Nachet No. 7) objective, bring the focus directly upon the line of separation between two minerals. On lowering the condenser and remov-

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* Ueber die Bestimmbarkeit der Gesteinsgemengtheile auf Grund ihres Lichtbrechunge Vermogens. *Wien. Acad.* 1893, 1.

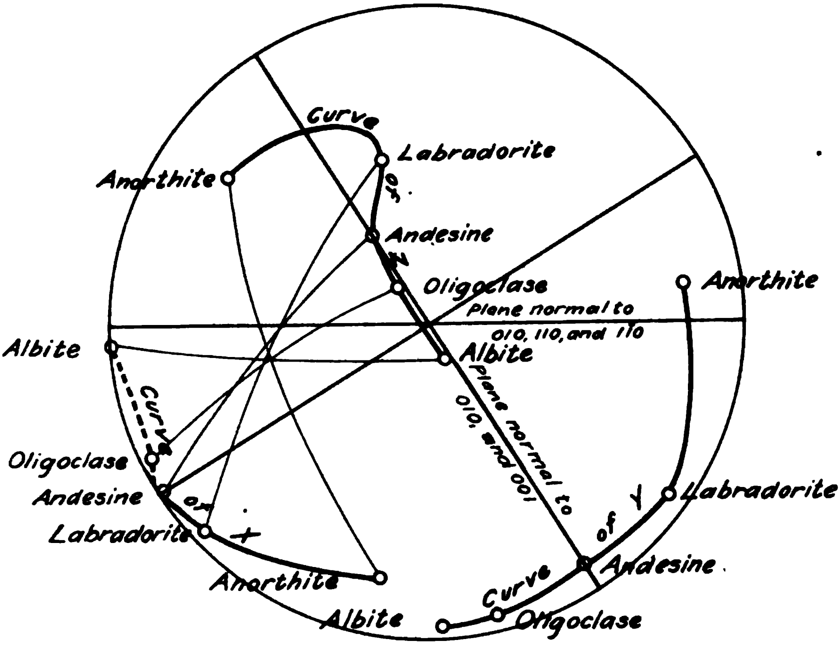

Fig. 93. Stereographic projection of the axes X, Y, Z in the plagioclase feldspars on the plane 010.

ing the analyzing nicol the field is a little darkened, but a very fine line of white light clearer and brighter than the grain on either side, accompanies sharply the line marking the contact of the two grains. When the objective is focused so that the line is bright, if the objective is raised very gently, and the least amount possible, this bright line moves a little toward the more refractive mineral, before it disappears. If the objective be lowered in the same way the white border line shifts a little toward the less refractive mineral. This is explained in full on page 10. This method is useful for distinguishing between orthoclase and quartz and between the fresh secondary plagioclases of the crystalline schists and quartz. By its means, also, the acid plagioclases may be distinguished from the basic plagioclases. It is to be employed with one condition, viz.: when two adjacent minerals of nearly the same refractive index happen to be cut, one perpendicular to X and the other to Z the movement of the line might be governed by the difference between $n_p$ and $n_g$ of the two minerals, rather than by the difference of their mean refractive indices. Therefore, for careful work it is advisable to use grains of definite known orientation, and thus secure a compar-

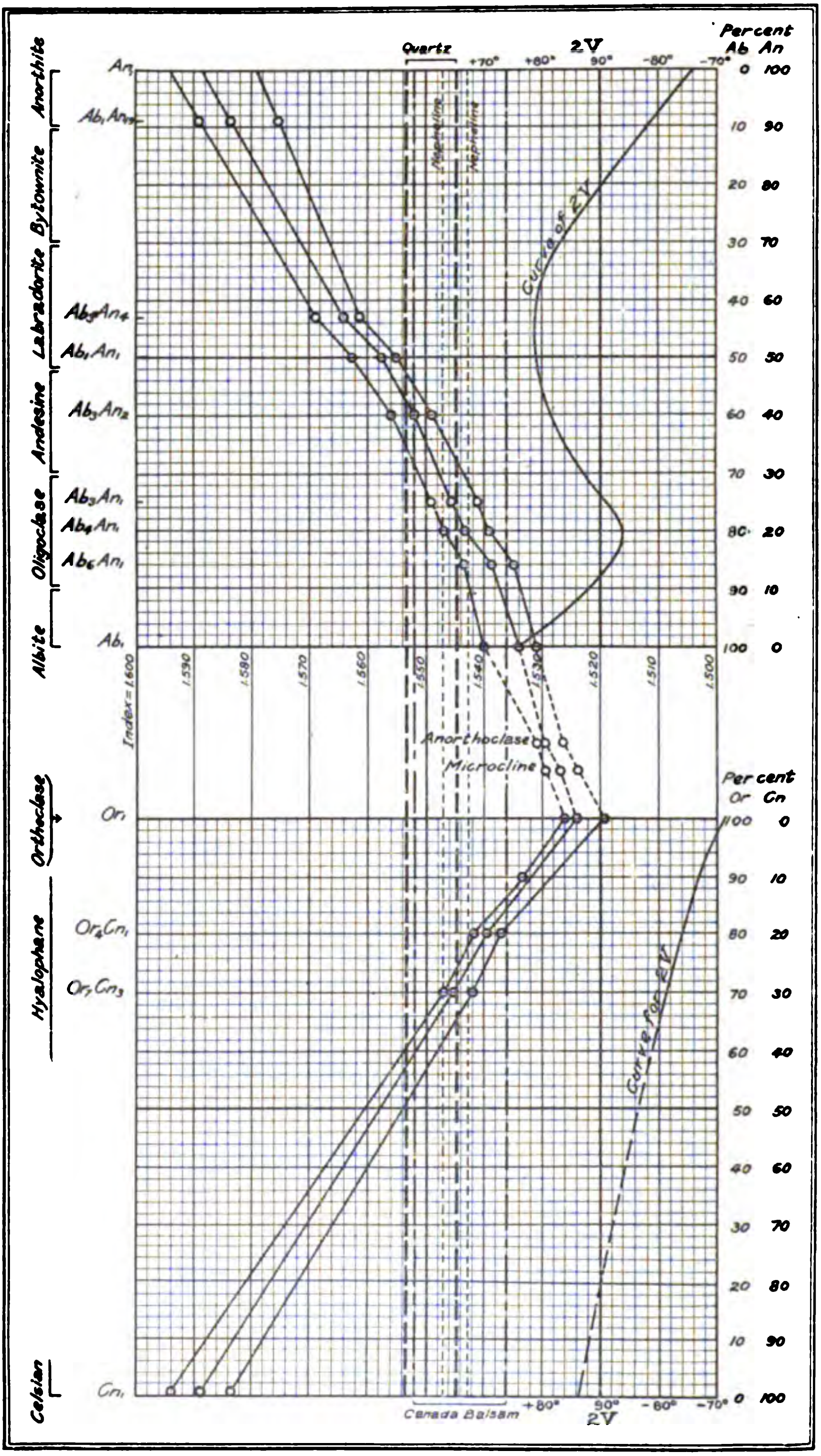

Fig. 94. Indices of refraction of the feldspars.

ison, not of mean indices, but of selected indices of the given minerals. The exact relations between the various indices of the feldspars and those of quartz, and nepheline, and Canada balsam are most conveniently expressed graphically, as in the diagram (figure 94). The index of Canada balsam varies with the concentration of the balsam by evaporation of water, but the value is usually about 1.545, and varies within the approximate limits shown in the diagram.

The refringence and birefringence of the feldspars may be tabulated as follows, all measures being in sodium light (except abnormal orthoclase, lithium light) :—

*Refringence and birefringence of the feldspars.*

| Name | Approx. Comp. | Refringence | | | Birefringence | | |
|---|---|---|---|---|---|---|---|
| | | $n_g$ | $n_m$ | $n_p$ | section ⊥X<br>$n_g - n_m$ | section ⊥Z<br>$n_m - n_p$ | section ∥Opt.Pl.<br>$n_g - n_p$ |
| Celesian | Cn | 1.5941 | 1.5886 | 1.5835 | 0.0055 | 0.0051 | 0.0106 |
| Hyalophane | (Or, Cn) | 1.5469 | 1.5451 | 1.5419 | 0.0018 | 0.0032 | 0.0050 |
| Normal orthoclase | Or | 1.5260 | 1.5237 | 1.5180 | 0.0023 | 0.0047 | 0.0070 |
| Abnormal orthoclase | Or | 1.5240 | 1.5239 | 1.5170 | 0.0001 | 0.0069 | 0.0070 |
| Soda orthoclase | (Or,Ab) | | 1.5282 | | | | >0.0070 |
| Microcline | Or | 1.5296 | 1.5264 | 1.5224 | 0.0032 | 0.0040 | 0.0072 |
| Anorthoclase | (Ab,Or) | 1.5305 | 1.5294 | 1.5234 | 0.0011 | 0.0060 | 0.0071 |
| Albite | Ab | 1.5400 | 1.5340 | 1.5310 | 0.0060 | 0.0030 | 0.0090 |
| Oligoclase-albite | $Ab_6An_1$ | 1.5433 | 1.5385 | 1.5346 | 0.0048 | 0.0039 | 0.0087 |
| Oligoclase | $Ab_4An_1$ | 1.5469 | 1.5431 | 1.5389 | 0.0038 | 0.0042 | 0.0080 |
| Oligoclase-andesine | $Ab_3An_1$ | 1.5490 | 1.5458 | 1.5417 | 0.0032 | 0.0041 | 0.0073 |
| Andesine | $Ab_3An_2$ | 1.5560 | 1.5530 | 1.5490 | 0.0030 | 0.0040 | 0.0070 |
| Labradorite | $Ab_1An_1$ | 1.5625 | 1.5578 | 1.5548 | 0.0047 | 0.0030 | 0.0077 |
| Basic labradorite | $Ab_3An_4$ | 1.5689 | 1.5639 | 1.5611 | 0.0060 | 0.0028 | 0.0078 |
| Bytownite | $Ab_1An_3$ | | | | | | |
| Anorthite | An | 1.5884 | 1.5837 | 1.5757 | 0.0047 | 0.0080 | 0.0127 |
| Quartz | | 1.5534 | | 1.5443 | | | 0.0091 |
| Canada balsam | varies e. g., 1.536-1.549 | | | | | | |

The angle of the optic axes, the dispersion, and the optic sign in the various species may be tabulated as follows:—

*The optic angle, sign, and dispersion of the feldspars.*

| Name | Approx. Comp. | Dispersion about Z | Sign | 2V | 2E | 2H |
|---|---|---|---|---|---|---|
| Celsian | Cn | $\rho<v$? | + | 87° | | 96° |
| Hyalophane | (Or,Cn) | $\rho<v$ | − | 79°± | | 83°± |
| Normal orthoclase | Or | $\rho<v$ | − | 0°-70°<br>usually 69°± | usually<br>119°-125° | |
| Abnormal orthoclase | Or | $\rho>v$ | − | small | | |
| Soda orthoclase | (Or,Ab) | | − | 70°+ | | |
| Microcline | Or | $\rho<v$ | − | 83°± | | 88°± |
| Microcline-anorthoclase | (Or,Ab | $\rho<v$ | − | 60°± | | |
| Anorthoclase | (Ab,Or) | $\rho<v$ | − | 32°-54° | 68°-88° | 45°-54° |
| Albite | Ab | $\rho<v$ | + | 77° | 150° | 82° |
| Oligoclase-albite | $Ab_8An_1$ | $\rho<v$ | − | 88° 30′ | | |
| Oligoclase | $Ab_4An_1$ | $\rho<v$ | − | 88° | | 94° |
| Oligoclase-andesine | $Ab_3An_1$ | $\rho<v$ | − | 86° | | |
| Andesine | $Ab_3An_1$ | $\rho<v$ | + | 88° | | 94° |
| Labradorite | $Ab_1An_1$ | $\rho>v$ | + | 77° | | 87° |
| Basic labradorite | $Ab_3An_4$ | $\rho>v$ | + | 79° | | |
| Bytownite | $Ab_1An_3$ | $\rho>v$ | ± | 90°± | | |
| Anorthite | An | $\rho>v$ | − | 77° 30′ | | 85° |

INCLUSIONS. The feldspars may contain inclusions, either gaseous, liquid, or solid, which are occasionally regularly placed; but in general these are not at all characteristic. However, inclusions are sometimes found which are more or less characteristic of certain varieties; they will be mentioned in the descriptions of the various species.

ALTERATIONS. Feldspars alter in many different ways which may be classed as follows, although the natural conditions leading to alterations are too complex to permit any simple classification, and the following tabulation is intended only as a general statement of the larger truths.

I. Alterations of the zone of katamorphism.
  1. Chiefly in the belt of weathering.
    1. Change to kaolinite, pyrophyllite, halloysite, etc.
    2. Change to hydrargillite, quartz, and calcite.

2. Chiefly in the belt of cementation.
    1. Change to zeolites.
    2. Change to prehnite.
    3. Change to glauconite.
    4. Changes of the belt of weathering, here subordinate.

II. Alterations of the zone of anamorphism.
   1. Change to damourite (or paragonite) sometimes with hydrargillite.
   2. Change to chlorite, or biotite.
   3. Change to quartz, calcite, and epidote.
   4. Change to albite, zoisite, muscovite, and quartz (saussurite).
   5. Change to scapolite.

III. Alterations due to acid fumaroles.
   1. Change to tourmaline, etc.
   2. Change to alunite.

IV. Alterations due to alkaline fumaroles.

V. Alterations due to heat alone.

VI. Alterations due to hot solutions.

The formation of kaolinite is more frequently found in the acid than in the basic feldspars. The kaolinite formed is usually in very small flakes which give a feldspar a cloudy, nearly opaque appearance. This is the ordinary method of origin of common clay, although its concentration in clay beds is sometimes accomplished by water transportation. Pyrophyllite is sometimes formed instead of kaolinite by this method of decomposition. When the process of hydration goes still further it may result in the formation of halloysite, montmorillonite, or other hydrous aluminum silicates.

Hydrargillite may be distinguished from the preceding alteration products by the distinctly oblique extinction in sections perpendicular to the cleavage, and by common polysynthetic twinning. It is found especially in basic igneous rocks, particularly affecting the microlites of basalts. It is commonly accompanied by such other alteration products as quartz and calcite.

Zeolites may result from the alteration of feldspars especially in basic rocks. The alteration sometimes involves solution, more or less transportation, and deposition in amygdaloidal cavities. In some cases the change is indirect: dipyre may form from the feldspar, and then give place to some zeolite; or, again, the zeolitization may begin in nepheline, or a related mineral, and gradually encroach on the feldspar.

The alteration to prehnite resembles the change to zeolites, with which the former is often associated. Calcite and quartz may also be formed under nearly the same conditions.

The alteration to glauconite is found in limestones, in which the clastic grains of orthoclase are sometimes impregnated with lamellæ of glauconite which gradually transform the whole grain to an aggregate of very fine, green laminæ. This alteration occurs today at the bottom of the sea under conditions which are not abnormal; glauconite[1] of the Tertiary limestones is probably in part of the same origin.

The alteration of the feldspars to mica is common, especially in the acid members of the group. The resultant mica is usually damourite, that is, a muscovite with a small optic angle. The flakes of mica are often of submicroscopic size; they form first along the cleavage planes. The mica is apparently sometimes paragonite. It is sometimes accompanied by the formation of secondary hydrargillite, quartz, and calcite. In pegmatite it may be accompanied by secondary quartz and albite.

The alteration of feldspars to some form of chlorite is not uncommonly seen in highly altered rocks; it is usually confined to the basic feldspars. All stages of the transformation can be found. A similar process probably leads sometimes to the formation of biotite. These minerals cannot form exclusively from feldspars; iron and magnesia are obtained from adjoining minerals.

The alteration of feldspar to a mass of quartz, calcite, and epidote is common. Such alterations are nearly always accompanied or followed by the introduction of more or less iron, chiefly as limonite.

Saussuritization is a process confined to regions of dynamic metamorphism. It is often accompanied by a banded schistose structure due to the pressure which the rocks have undergone. It is a change which is known to affect gabbros only. The basic feldspars of these rocks are thereby transformed to masses containing zoisite, epidote, some acid feldspar, and quartz, with tremolite or actinolite, sometimes with garnet and rutile, more rarely scapolite and calcite. The pyroxene of the gabbro is changed at the same time to green amphibole or to glaucophane.

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[1] Glauconite is probably also produced in large amount through the agency of various kinds of organisms.

The alteration to scapolite has been studied in great detail in the rocks of the Pyrenees by Lacroix[1]. The peculiar feature of the process is that a single crystal of dipyre may form from a large number of feldspar crystals thus giving rise to a rock of much coarser grain than its parent. This alteration may be due to regional metamorphism in some cases, but Lacroix has found abundant evidence that it is not always due to this cause. It is nearly always accompanied by the uralitization of the pyroxene.

Acid fumaroles change feldspars to tourmaline, to cassitterite, to kaolinite with cassiterite, etc. In other cases the process results in the formation of alunite, often with native sulphur. The results of the action of alkaline fumaroles are not so easily recognized. They may be seen in rock fragments enclosed within acid volcanic rocks. The feldspars of these fragments are often corroded and then enlarged by a new growth of soda-orthoclase oriented on the old feldspar.

Alterations due to heat alone result in the opening of the feldspars along their cleavage planes and their partial fusion and recrystallization. This process often charges the feldspars with gaseous and vitreous inclusions; it also changes normal orthoclase to the abnormal type.

It is noticeable that the same minerals occur as alteration products under different conditions in the foregoing divisions. This is due largely to the fact that all the factors producing alteration cannot be stated in a simple classification. Thus, it has been recently shown that hot solutions produce alterations that are to some extent independent of depth. The chief products of such alterations are quartz, damourite (or sericite), chlorite, albite, and adularia. The alterations due to fumaroles are also abnormal products in the zone of katamorphism.

Alterations of feldspar may be followed by regeneration of the same or, more commonly, another variety of feldspar. In this way feldspar grains or crystals are sometimes much enlarged. The new feldspar is fresh and glassy, while the old is more or less permeated by alteration products. The old feldspar may be abnormal orthoclase and the new normal orthoclase; the old may be calcosodic feldspar and the new pure albite, or even adularia. Such changes occur in all kinds of rocks.

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[1] *Bull. Soc. Min. Fr.* 1891. XIV. 16.

OCCURRENCE. The feldspars are the most abundant and most widely distributed minerals of the earth's crust. They serve as a basis of classification of the igneous rocks; they are almost as abundant in the metamorphic rocks, and even the sedimentary rocks often contain clastic feldspars. They are a normal product of crystallization of all the common igneous magmas; they are a common product of metamorphism, both contact and regional; finally, they are often formed in veins from hot solutions, and in pegmatite dikes under aqueo-igneous conditions.

DIAGNOSTICS. Feldspars are the most abundant colorless constituents of igneous rocks; they are distinguished from quartz by the presence of cleavage and twinning and by their biaxial character. They are also characterized by low refringence and weak birefringence. They alter readily, as described above. To distinguish between the various feldspars, recourse must be had to the extinction angles in various sections or zones, to the optic sign, to the presence or absence of polysynthetic twinning (plagioclase or orthoclase), to the refringence (especially as compared with quartz by the Becke method), to the birefringence (especially anorthite), to the specific gravity, or to the precise chemical composition. Still other means are occasionally available; those of importance will be mentioned in the description of each species.

### (a) *Extinctions on the base and brachypinacoid.*

Schuster* and Mallard established the relations existing between the extinction angles on the base and the brachypinacoid, and the changing acidity of the plagioclases (p. 212). The prevalence of favorable cleavages renders it a simple matter to obtain plates parallel to these faces. For purposes of determination it is usually necessary only to make a coarse powder from one of the crystals, from which may be selected such cleavage fragments as afford these two directions. These may be distinguished not only by the difference in the facility of the cleavage but also by the different interference figures given in convergent light. Cleavage pieces parallel to 001 will appear larger and more abundant than those parallel to 010. They will be apt to show some trace of the albite striation, and they will never show a bisectrix, but instead will exhibit the indefinite extinction characteristic of Y. Anorthite comes nearest to exhibiting a bisectrix in a basal section. On the contrary cleavage fragments parallel to 010 are likely to have two straight parallel edges, caused by the easy basal cleavage. These should not be confounded with basal fragments bounded by the brachypinacoidal cleavages. At the same time if the fragments be parallel to 010 they will invariably reveal a bisectrix Z either perpendicular or somewhat inclined to the axis of the microscope when examined in convergent light. To this statement the basic plagioclases (labradorite to anorthite) may be considered an exception, inasmuch as the inclination of the axis Z is so great that the point at which it pierces the plane of the section is outside of the field of the microscope. But a test will still show that the nearest bisectrix is Z.

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* Ueber die optische Orientirung der Plagioclase, *Min. Pet. Mitt.* (*Tschermak*), 1880, III, 117-284.

Sur l'isomorphisme des feldspaths tricliniques, *Bull. Soc. Min. France*, 1881, IV, p. 103.

When the examination has to do with the microlitic feldspars of the second consolidation, it is usually impossible to obtain cleavage fragments for the foregoing process. It is then necessary to search for favorable sections cut at random in a thin section of the rock when the same distinctions are to be observed, or resort may be had to the methods mentioned below. Sections parallel to 010 do not show the albite twinning lines.

In general, when the extinction angles on both 001 and 010 are large that fact indicates bytownite or anorthite; when both are small the feldspar is either oligoclase or andesine. Intermediate extinction angles are seen in albite and labradorite; while the potash and soda-potash feldspars have extinction on 001 practically parallel to the cleavages (except microcline which has extinction at 15° 30′), and on 010 their extinction varies from 5° to 9°.

The extinction angles of the feldspars on the base and the brachypinacoid (or clinopinacoid) are given in the table on page 212.

(b) *The Statistical Method.*

The method proposed by Michel Lévy, often designated the *statistical method**, is applicable to all cases in which cleavage pieces of sufficient size cannot be obtained, but in which still the albite twinning is evident. Since the albite twinning forms lamellæ parallel to the face 010, whose edges are inclined to each other alternatingly outward and inward, a thin section cutting these lamellæ at right angles to 010 would cut them also at right angles, and the extinction angles on opposite sides of any twinning line would be equal, but of contrary signs since one lamella is turned 180° from the conventional position about a line perpendicular to 010, (p. 193). In case the section be not cut in a plane perpendicular to 010 the extinction on one side of the twinning line is greater than on the other. The method consists in finding the *maximum equal extinctions* on opposite sides of an albite twinning line. All sections that have equal extinctions on adjacent sides of a twinning line in the same species, are cut perpendicular to the face 010; but only one of these affords the maximum equal extinctions. The position of the plane which affords the maximum extinctions in the zone perpendicular to 010, is different for the different species, and the maxima also differ for the different species. When this maximum has been found it serves for the index to the species according to the tabulation on page 212.

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* De l'emploi du microscope polarisant à lumière parallel pour l'étude des plaques minces des roches éruptives. *Ann. des Mines*, Dec. 1877, pp. 392 to 471 (V. p. 451).

In the application of this method it is not necessary to examine all sections of the feldspars at random, but by certain guides those in the zonal position can be selected. (1) It is the zone of symmetry of the albite twinning, and the alternate lamellæ extinguish at the same angle. (2) Since the sections of this zone are perpendicular to the composition face of the albite twinning, these twinning lines are extremely fine, and remain immovable when the focus of a high power objective is raised through the thickness of the section. Such sections are also perpendicular to the feldspathic microlites, which seem to be elongated parallel to the albite twinning lines, because they are flattened parallel to 010 (see figures 74 and 75). (3) Sections perpendicular to 010 may also be identified by the fact that the twinned parts show equal illumination eight times in a complete revolution, viz. four times when the twinning line is parallel with either cross hair, and four times at 45° from the cross hairs. In these positions the lamellæ appear to belong to a single crystal, being separated only by a very fine dark line, sometimes almost invisible. This test is extremely delicate, and with the least obliquity to the axis of the zone the equal luminosity does not appear.

This method, notwithstanding its tediousness, is one of the most serviceable as well as most reliable, owing to the readiness with which sections perpendicular to the plane 010 can be recognized, and to the characteristic differences in the maxima of the various feldspars. The chief obstacles that interfere with its use are (1) the possible existence of two or more feldspars in the same thin section, and (2), the possible non-existence of the maximum equal extinction in any of the crystals cut by the random section. The former is more likely to arise in the examination of the acid and metamorphic rocks, and the latter in the case of a limited number of feldspar sections in the rock cut. In the presence of two or more feldspars, however, usually they will be found to differ in transparency or in mode of distribution, or in other evident optical characters, and the error can be obviated. In the case of the feldspathic microlites they are almost invariably of the same species when formed rapidly at the second consolidation. The second obstacle can only be reduced by increasing the number of feldspar sections subjected to inspection.

These maxima, alone, are sufficient to identify the oligoclases (0° to 5°), the basic andesines (more than 16°, less than 22°), the labradorites (from 22° to 35°), the bytownites (from 35° to 45°) and the anorthites (above 45°).

When the feldspar microlites are twinned on the albite plan, as frequently happens, they are amenable to this process of examination. When they are simple their determination is more difficult. It has been proposed by Michel-Lévy, in that case, to employ the zone 001 : 010 parallel to the axis of which they have their longest dimension, but the results obtained are not sufficiently characteristic for all the species. Extinctions of such microlites, referred to their longer dimension, are tabulated on page 212.

Microcline, some forms of labradorite, and albite could hardly be distinguished by their maximum extinctions in simple microlites, but orthoclase, oligoclase and anorthite are characterized by maxima which are sufficiently distinct. Microcline, however, is rarely or never seen in the condition of microlites, while the associations of labradorite and albite are so different that there is little danger of confounding them. Labradorite is the commonest product of the consolidation of the basic eruptives and albite almost invariably results from metamorphism, frequently from the contact of igneous rocks on the calcareous clastics.

There is very little reason to expect, side by side, microlites of different natures. In the vast majority of cases the microlites are formed rapidly, and present a great preponderance of a single species of plagioclase.

(c) *Sections perpendicular to the bisectrices.*

This method of determination requires the use of convergent light and the careful observation of the interference figure of the bisectrices. It is well also, but not always necessary, to place a drop of iodide of methyl, or of glycerine, on the lens of the objective, and another on the upper lens of the condenser, in order that, when they are both brought near the slide holding the section, the liquid will spread to the right and left, producing practical immersion. This increases the field of possible observation without deranging the geometric relations.

The details of this method have been elaborated by Fouqué.* It may at first sight appear to be a difficult task to obtain sections perpendicular to the bisectrices Z or X. But when it is remembered that cleavage pieces or sections cut parallel to 010 will nearly always show the axis Z, and when not perpendicular may be made so by a little oblique grinding, or by the use of the tilting stage of Federov, constructed by Nachet, and also that the axis X is in the vicinity of the edge 001 : 010, it is evident that but little manipulation is necessary to cut a crystal perpendicular to either axis. Small transparent crystals are necessary, or pieces of large crystals bounded by known cleavages. The little crystal is encased in a ball of thick Canada balsam which can be molded at will. This is allowed to swim in a little glass ring. Observed thus in convergent polarized light the crystal is brought to present the orientation in which it gives the figure of the axis sought. The operation is facilitated by the previous knowledge of its cleavages, and of the probable nature of the species in hand.

The axis X is preferable in the examination of the acid plagioclases, and Z in that of the basic. Fouqué ascertained by the examination of numerous inclined sections that in case of slight obliquity, the decentering of the image and the consequent error in the result, is less in sections perpendicular to X than in those perpendicular to Z. He also ascertained that the error is greater (except in the basic feldspars) when the inclination is in the direction of the trace of the plane of the optic axes than in a direction perpendicular to it. An inclination of 5° removes the figure one-third of the radius of the field of the microscope away from the central position. An inclination of 10° removes it two-thirds of the same radius.

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* Contribution à l'étude des feldspaths des roches volcaniques. *Bull. Soc. Min. France*, Vol. XVII, 1894, pp. 283-611. Also issued separately with independent paging.

When a bisectrix is found and its orientation with respect to X and Z determined, it remains to measure the extinction angle with a trace of a known crystallographic character. This angle is that made by the optic plane with a twinning (albite) lamella, or with the cleavage parallel to 001. Sections perpendicular to X are always measured, for this angle, on the albite twinning, or, which is the same thing, on the cleavage 010. In the case of sections perpendicular to Z the same crystallographic character is employed in examining the basic feldspars, but it is necessary to have recourse to some other character for the acid feldspars in which the plane perpendicular to Z is parallel, or nearly parallel, to the face 010, rendering the cleavage 010 and the albite twinning invisible. In such a case extinction is measured on the cleavage parallel to 001 which is very rarely wanting in the acid feldspars.

The extinction angles for the various feldspars in sections perpendicular to the bisectrices are given in the table on page 212. Extinction angles ranging from 55° to 88° indicate that the section is normal to X; those between 48° and 3° indicate that it is perpendicular to Z.

The extinction angles referred to on the preceding pages may be tabulated together for convenience of reference as follows:—

*Important extinction angles of the feldspars.*

| Name | Extinction Section ∥ 001 | Extinction Section ∥ 010 | Extinction based on trace of optic plane |  | Maximum equal extinction Zone ⊥ 010 | Maximum extinction Zone ∥ *a* Microlites |
|---|---|---|---|---|---|---|
|  |  |  | Section (-) ⊥X α | Section (+) ⊥ Z c |  |  |
| **Celsian** | 0° | +28° | 0° | 90° | 0° | 28° |
| **Hyalophane** | 0° | − 5° to −24° | 90° | 5°-24° | 0° | 5°-24° |
| **Normal orthoclase** | 0° | + 5° | 90° | 5° | 0° | 5° |
| **Abnormal orthoclase** | 0° | + 5° | 0° | 90° | 0° | 5° |
| **Soda orthoclase** | 0°? | +11° | 90°? | 11° | 0°? | 11° |
| **Microcline** | +15° | + 5° | 88° | 10° | +19° | 16° |
| **Microcline -anorthoclase** | + 2° to + 5° | + 9° | 89° | 5°-8° |  |  |
| **Anorthoclase** | + 1½° | + 4° to +10° | 89° | 9° | 1°-2° |  |
| **Albite** | + 4° | +20° | 74° | 20° | −16° | 20° |
| **Oligoclase -albite** | + 2½° | +10½° | 84½° | 10½° | − 4° |  |
| **Oligoclase** | + 2° | + 7° | 88° | 5° | + 2° | 0½° |
| **Oligoclase -andesine** | 0° | 0° | 75° | 3° | + 7° | 0° |
| **Andesine -oligoclase** | − 2° | − 4° | 70° | 3° | +16° |  |
| **Andesine** | − 2½° | −10° | 66° | 9° | +25° | 7° |
| **Labradorite** | − 5½° | −20° | 60° | 22° | +34° | 18° |
| **Basic labradorite** | −11° | −25° | 58½° | 33° | +37° | 32° |
| **Bytownite** | −18°± | −33° | 57° | 42° | +43° |  |
| **Anorthite** | −37° | −42° | 55° | 48° | +56° | 55° |

CLASSIFICATION. Since celsian has recently been shown to be monoclinic,[1] and related to hyalophane, the feldspars may be classified as follows:

Monoclinic Feldspars

| | | |
|---|---|---|
| Monoclinic feldspars | Celsian | $BaAl_2Si_2O_8$ |
| | Hyalophane | $mBaAl_2Si_2O_8+nKAlSi_3O_8$<br>(often $(K_2,Ba)Al_2Si_4O_{12}$) |
| | Orthoclase | $KAlSi_3O_8$ |
| | Soda-orthoclase | $(K,Na)AlSi_3O_8$ |

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[1] J. E. Strandmark. *Geol. Foeren. Stockh. Foerhandl.* XXV. p. 289. 1903. Summarized in *Neues Jahrb. Min. Geol. Paleon.* 1904. II. p. 175.

Triclinic Feldspars

| | | | |
|---|---|---|---|
| Pseudomonoclinic feldspars | Microcline | | $KAlSi_3O_8$ |
| | Microcline-anorthoclase | | $(K,Na)AlSi_3O_8$ |
| | Anorthoclase | | $(Na,K)AlSi_3O_8$ |
| Plagioclase feldspars | Albite | | $NaAlSi_3O_8$ |
| | Oligoclase | $(Ab_{12}An_1$ to $Ab_3An_1)$ | $mNaAlSi_3O_8$ $+nCaAl_2Si_2O_8$ |
| | Andesine | $(Ab_2An_1$ to $Ab_4An_3)$ | |
| | Labradorite | $(Ab_1An_1$ to $Ab_1An_2)$ | |
| | Bytownite | $(Ab_1An_3$ to $Ab_1An_8)$ | |
| | Anorthite | | $CaAl_2Si_2O_8$ |

## CELSIAN.

MONOCLINIC $a:b:c::0.657:1:0.554$ $BaAl_2Si_2O_8$

$\beta = 115° 2'$

PHYS. CHAR. Crystal forms similar to those of orthoclase (adularia). Twinning according to Carlsbad, Manebach, and Baveno laws. Cleavages || 001 and 010. G. = 3.38. H. 6.-6.5. Infusible. Soluble in HCl.

OPT. PROP. The plane of the optic axes is parallel to 010; the positive acute bisectrix Z makes an angle in this plane of 28° with the lateral axis *a* in the obtuse angle $\beta$. The optic normal is therefore perpendicular to the cleavage 010.

$$(+) \quad 2V = 87° \pm$$

$$n_g = 1.5941 \quad n_m = 1.5886 \quad n_p = 1.5835$$

$$n_g - n_p = 0.0106$$

Colorless, or stained by impurities. Luster vitreous. Colorless in thin section.

OCCUR. Celsian is distinctly a mineral produced by contact metamorphism; it is found in dolomite cut by trap, associated with garnet, manganophyllite, and schefferite. Rare.

DIAG. Distinguished from orthoclase and hyalophane by the optic sign and higher refringence. Also characterized by large extinction angle in section parallel to 010, rather strong birefringence and large optic angle; further by solubility and high specific gravity.

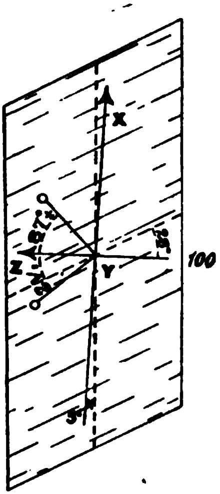

Fig. 95.
Optical orientation of celsian.

## HYALOPHANE.

MONOCLINIC $a:b:c::0.6584:1:0.5512$ $(K_2,Ba)Al_2Si_4O_{12}$

$\beta = 115° 34\frac{1}{2}'$

PHYS. CHAR. Crystal forms similar to orthoclase (adularia).

Perfect cleavage || 001; very good cleavage || 010. H. = 6.-6.5. G. = 2.8. Difficultly fusible. Insoluble in acids.

**Opt. Prop.** The plane of the optic axes and the obtuse bisectrix are normal to 010. The extinction angle on 010 varies from —5° to about —24°, probably with increase of barium content, since in celsian the angle is still greater. Distinct horizontal dispersion with $\rho > v$ weak.

| | $Ce_3Or_7$ | $Ce_1Or_4$ |
|---|---|---|
| (—) $2V =$ | 79° | 74° |
| $n_g =$ | 1.5469 | 1.5416 |
| $n_m =$ | 1.5451 | 1.5395 |
| $n_p =$ | 1.5419 | 1.5373 |
| $n_g - n_p =$ | 0.0050 | 0.0043 |

Colorless, white, greenish, reddish. Luster vitreous. Colorless in thin section.

**Occur.** Found in dolomite in manganese mines in Sweden; also in dolomite elsewhere. Apparently a contact mineral.

**Diag.** Distinguished from orthoclase by the extinction angle on 010; also by higher specific gravity and presence of barium.

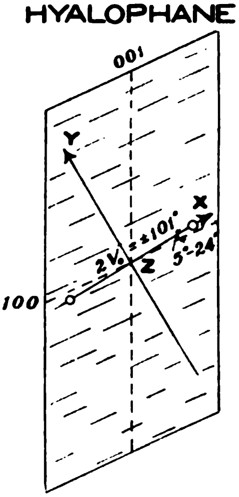

Fig. 96.
Optical orientation of hyalophane.

## ORTHOCLASE.

Monoclinic $a : b : c :: 0.6586 : 1 : 0.5559$ $KAlSi_3O_8$

$\beta = 116° 3'$

**Phys. Char.** Crystals of orthoclase commonly have the forms named in the description of the feldspar group. Carlsbad

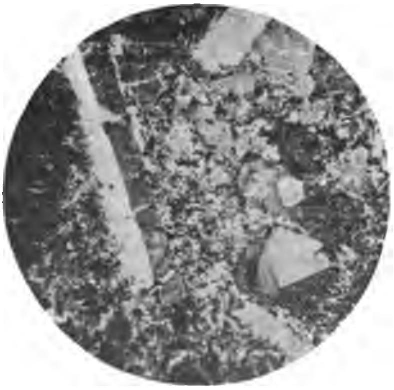

Fig. 97. Section of orthoclase showing Carlsbad and Baveno twinning in trachyte from Monte di Vetta, Italy. U. W. 810. + nicols. × 10.

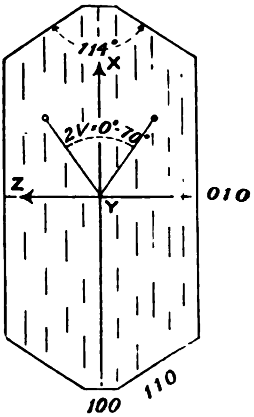

Fig. 98.
Optical orientation of normal orthoclase in a basal section.

twinning is frequent; Baveno and Manebach twinning infrequent. Cleavage perfect || 001, very good || 010. Other cleavages or parting planes occasionally seen are || $1\bar{1}0$ and 100. H. = 6. G. = 2.55-2.58. Fusible at 5. Insoluble in acids.

Opt. Prop. *Normal Orthoclase.* The plane of the optic axes and the obtuse bisectrix are normal to 010; the trace of the optic plane makes an angle of + 5° with the cleavage of 001. The angle of the optic axes is very variable; it seems to be larger in orthoclase of the plutonic rocks than in that of the volcanic. The angle $2V$ is usually about 69° in the former. Distinct horizontal dispersion with $\rho > v$.

$$(-)\ 2V = 0^\circ \text{ to } 70^\circ$$

$$n_g = 1.5260 \quad n_m = 1.5237 \quad n_p = 1.5190$$

$$n_g - n_p = 0.007$$

Colorless, white, pink, red, yellow, gray, green. Luster vitreous. Colorless in thin section.

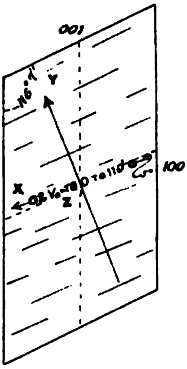

Fig. 99.
Optical orientation of normal orthoclase in a clinopinacoidal section.

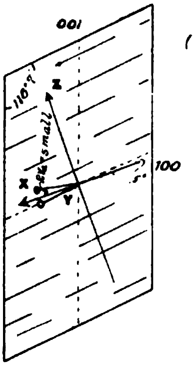

Fig. 100.
Optical orientation of abnormal orthoclase.

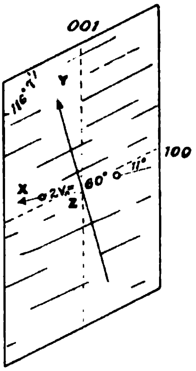

Fig. 101.
Optical orientation of soda orthoclase.

*Abnormal Orthoclase.* When normal orthoclase is highly heated the angle of the optic axes gradually diminishes with increasing temperature until finally it becomes 0°; then the optic axes gradually separate again in a plane perpendicular to the former position, and parallel to 010. This change is reversible if the temperature is not raised above 600°C. Above that temperature the change becomes permanent. Orthoclase which has been subjected to a high temperature in nature therefore shows this abnormal position of the optic axes. In some cases the plane of the optic axes may be perpendicular to 010 for red light and parallel to 010 for blue light. In abnormal orthoclase the angle of the optic axes is always small Inclined dispersion slight with $\rho > v$. Colorless.

$$(-)\ 2V = \text{small angle}$$
$$n_g = 1.5240 \quad n_m = 1.5239 \quad n_p = 1.5170$$
$$n_g - n_p = 0.007$$

*Soda-orthoclase.* Similar to normal orthoclase, but the extinction in sections parallel to 010 attains 11°. The birefringence is slightly greater than in normal orthoclase, and the angle of the optic axes is usually larger according to Lacroix, but Fouqué gives $2V = 40°$ in one case. Colorless. See figure 101.

$$(-)\ 2V = 70° +$$
$$n_m = 1.5282$$
$$n_g - n_p = 0.007+$$

*Isorthoclase.* Duparc[1] has recently descrcibed a new variety of orthoclase which he calls *"Isorthose"* in which the acute bisectrix is Z, and which is therefore positive. The orientation is otherwise like that of normal orthoclase, the acute bisectrix being normal to 010. The optic angle is small, the hyperbolas not entirely leaving the field. The extinction angle in sections parallel to 010 is from 6° to 9°. Colorless.

ALTER. Orthoclase alters most commonly to kaolinite or damourite. Quartz and epidote may form at the same time. Much more rarely the alteration is to chlorite, to a zeolite, or, under exceptional conditions, to glauconite, to tourmaline, or to alunite. When heated, abnormal orthoclase is produced; when fused and recrystallized, soda-feldspar is often produced.

OCCUR. Extremely abundant in acid igneous rocks; present in igneous rocks of intermediate acidity; common in contact zones and in metamorphic rocks in general; found in clastic rocks, and in veins. Regular intergrowths of orthoclase and albite forming the so-called "perthite" are common; intergrowths of quartz with orthoclase, or other feldspar, often occur.

DIAG. Of all the feldspars orthoclase has the smallest optic angle, though anorthoclase has a smaller optic angle than the maximum of orthoclase; it has, further, the lowest specific gravity and the lowest refringence. Being monoclinic, it has no polysynthetic twinning, and the cleavage angle is exactly 90°.

## MICROCLINE.

TRICLINIC $a:b:c::0.6495:1:0.5546$ $KAlSi_3O_8$

$$\alpha = 90°\,7' \quad \beta = 115°\,50' \quad \gamma = 89°\,55'$$

PHYS. CHAR. Very similar to orthoclase. Macroscopic twinning according to the Carlsbad, Manebach, and Baveno laws; microscopic polysynthetic twinning constant according to the albite and pericline laws. The trace of the composition face of the pericline twinning makes an angle of +99° with 001 in 010. Cleavage perfect || 001, very good || 010, sometimes distinct || 110, rarely present less distinctly || 1$\bar{1}$0. H. = 6.-6.5. G. = 2.54-2.57. Fusible at 5. Insoluble in acids.

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[1] *Comptes Rendus.* 1904. CXXXVIII. p. 714.

Opt. Prop. The plane of the optic axes and the obtuse bisectrix are nearly perpendicular to 010; the negative acute bisectrix makes an angle of +5° in 010 with the trace of 001. The extinction angle in 001 is about +15° measured on the cleavage 010. The extinction angle referred to the trace of the optic plane in a section normal to X is 88°, and in a section normal to Z is 10°. The optic angle is large. Horizontal dispersion notable with $\rho > v$.

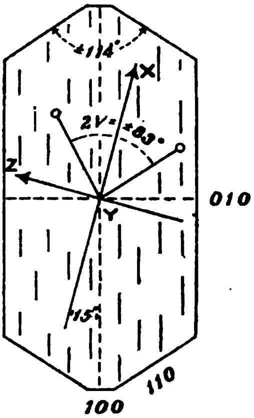


**Fig. 102.**

Optical orientation of microcline in a basal section.

**MICROCLINE**

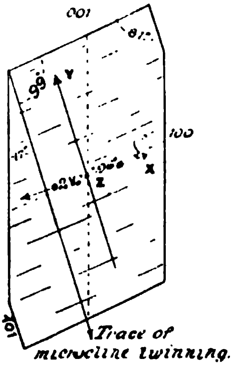


**Fig. 103.**

Optical orientation of microcline in a brachypinacoidal section.

$$(-)\ 2V = 83° \pm$$
$$n_g = 1.5296 \quad n_m = 1.5264 \quad n_p = 1.5224$$
$$n_g - n_p = 0.0072$$

Color white, yellowish, gray, green, red. Colorless in thin section; in thick sections the variety amazonstone shows pleochroism with Z colorless, Y sea green, and X very pale green.

Pericline twinning in the plagioclase feldspars makes a small angle with 001 and is therefore invisible in sections parallel to 001; in microcline the pericline twinning makes approximately a right angle (+99°) with 001 and therefore in sections parallel to 001 the pericline twinning (as well as the albite twinning) is distinct. These two types of polysynthetic twinning cross practically at right angles in sections parallel to 001 and produce a quadrille structure that is constant and quite characteristic of microcline.

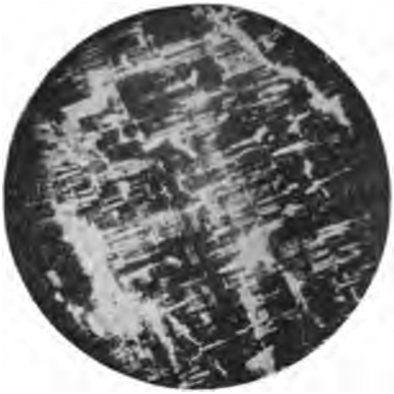


Fig. 104. Section of microcline showing quadrille structure. + nicols. × 45.

ALTER. Similar to those of orthoclase. Change to albite (with accompanying production of quartz and muscovite) especially common.

OCCUR. Similar to those of orthoclase but especially abundant in pegmatite. Regular intergrowths of microcline with other feldspars are common, especially with albite, orthoclase, and anorthoclase.

**Microcline-anorthoclase** [$(K.Na)AlSi_3O_8$] is like microcline in physical characters. The plane of the optic axes is almost perpendicular to 010, and other optic properties are similar to microcline and anorthoclase. The composition face of the pericline twinning makes an angle of +107° with the face 001. The extinction angle in sections normal to Z is 5° to 8° referred to the trace of the optic plane, and in sections normal to X it is 88½°. Colorless. (—) $2V = 56°\text{-}62°$. It is thus intermediate in optical characters between microcline and anorthoclase. It is uncommon.

DIAG. Microcline is characterized by quadrille structure of two rectangular polysynthetic twinning laws in sections parallel to 001, with extinction angle in same section of 15°.

## ANORTHOCLASE.

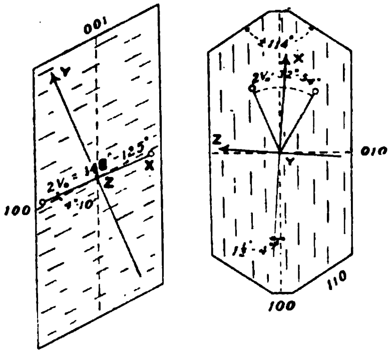
TRICLINIC $a : b : c :: 0.6466 : 1 : 0.5522$ $(Na,K)AlSi_3O_8$

$\alpha = 90\frac{1}{2}° \quad \beta = 116°\ 18' \quad \gamma = 90° \pm$

PHYS. CHAR. Similar to those of orthoclase. Cleavage perfect || 001, very easy || 010. H. = 6.-6.5. G. = 2.56-2.60.

OPT. PROP. The plane of the optic axes is almost perpendicular to 010. The negative acute bisectrix makes an angle of +4° to +10° in

**ANORTHOCLASE**



Figures 104a, 104b. Optical orientation of anorthoclase in brachypinacoidal and basal sections.

010 with the trace of 001. The extinction angle in cleavage pieces parallel to 001 is 1½°, parallel to 010 usually about 9°. The extinction angle referred to the trace of the optic plane in sections normal to Z is near 9°. normal to X, 89°. Distinct horizontal dispersion with $\rho > v$. Colorless.

$$(-)\ 2V = 42° \text{ to } 54° \text{ (rarely } 32°)$$

$$n_g = 1.5305 \quad n_m = 1.5294 \quad n_p = 1.5234$$

$$n_g - n_p = 0.0071$$

The quadrille or grating structure which is constant in microcline is sometimes absent in anorthoclase, due to the absence of pericline twinning. When present the twinning bands are usually very fine and much narrower than in microcline. The composition face of the pericline twinning makes an angle of —75° to —78° with 001 in 010.

The close relation and gradual gradation of optical properties corresponding to a gradation in chemical composition which exists in the plagioclase feldspars does not exist, or at least, has not yet been established, in the soda-potash feldspars.

Alter. The methods and products of alteration of anorthoclase are similar to those of orthoclase.

Occur. Always accompanied by orthoclase, and often intergrown regularly with it. Found in igneous rocks.

Diag. Quadrille structure is not so common as in microcline, and the bands are finer; the extinction in sections parallel to 001 is near 2° (instead of 15°, as in microcline); the optic angle is small; and the maximum equal extinction angle in the zone normal to 010 is 1° to 2°.

## Plagioclase Subgroup.

Phys. Char. The physical characters of these minerals have been described with those of the feldspar group as a whole. Albite twinning of many individuals is almost always present. This twinning is often combined with Carlsbad twinning, less frequently with Baveno, Manebach, etc. Polysynthetic pericline twinning is also common, usually recognizable only by the aid of the microscope.

Albite, oligoclase and andesine are not affected by acids, except by hydrofluoric acid; labradorite is attacked after long treatment, while anorthite is easily decomposed. The surface of the microscopic preparation, free from Canada balsam, may be treated for several hours at a temperature not exceeding 40° (Centigrade) in order to avoid melting the Canada balsam on the other side by which it is adherent to the glass slide; anorthite leaves a skeleton of silica, while labradorite only shows a partial corrosion. The test can be made on a fine powder, and greater heat applied, even to boiling of the acid. The partial attack on labradorite can be made apparent by applying to the slide, after thorough washing in water, some aniline color (as malachite green) which will permanently color the gelatinous silica.

Opt. Prop. The position of the optic elements has been given in the description of the feldspar group as a whole, but it may be repeated that in the plagioclase series the direction Z of the index of refraction $n_g$ is more or less nearly perpendicular to 010; therefore a bisectrix, more or less well centered, is seen in cleavage fragments parallel to 010 (only one hyperbola is seen in labradorite, bytownite and anorthite); Z is always in or very near the plane perpendicular to 010 and 001. The positions of Z and X are shown in the following table:—

*Orientation of Z and X in the plagioclase feldspars.*

| Name | Approximate Composition | Angle between Z and a normal to | | Angle between X and a normal to | |
|---|---|---|---|---|---|
| | | 001 | 010 | 001 | 010 |
| Albite | Ab | 78° | 16° | 89° | 81° |
| Oligoclase | $Ab_4An_1$ | 94° | 1° | 96° | 89° |
| Oligoclase–andesine | $Ab_8An_1$ | 80° | 6° | 91° | 90° |
| Andesine | $Ab_3An_2$ | 69° | 17° | 83° | 86° |
| Labradorite | $Ab_1An_1$ | 58° | 28° | 74° | 82° |
| Basic labradorite | $Ab_3An_4$ | 50° | 37° | 67° | 71° |
| Anorthite | An | 40° | 47° | 55° | 58° |

It will be seen that in acid plagioclase X is approximately parallel to the intersection of 001 and 010; in basic plagioclase it varies considerably from this position. These facts are shown in stereographic projection in figure 105, and figures 109-115.

The position of the optic elements with respect to the

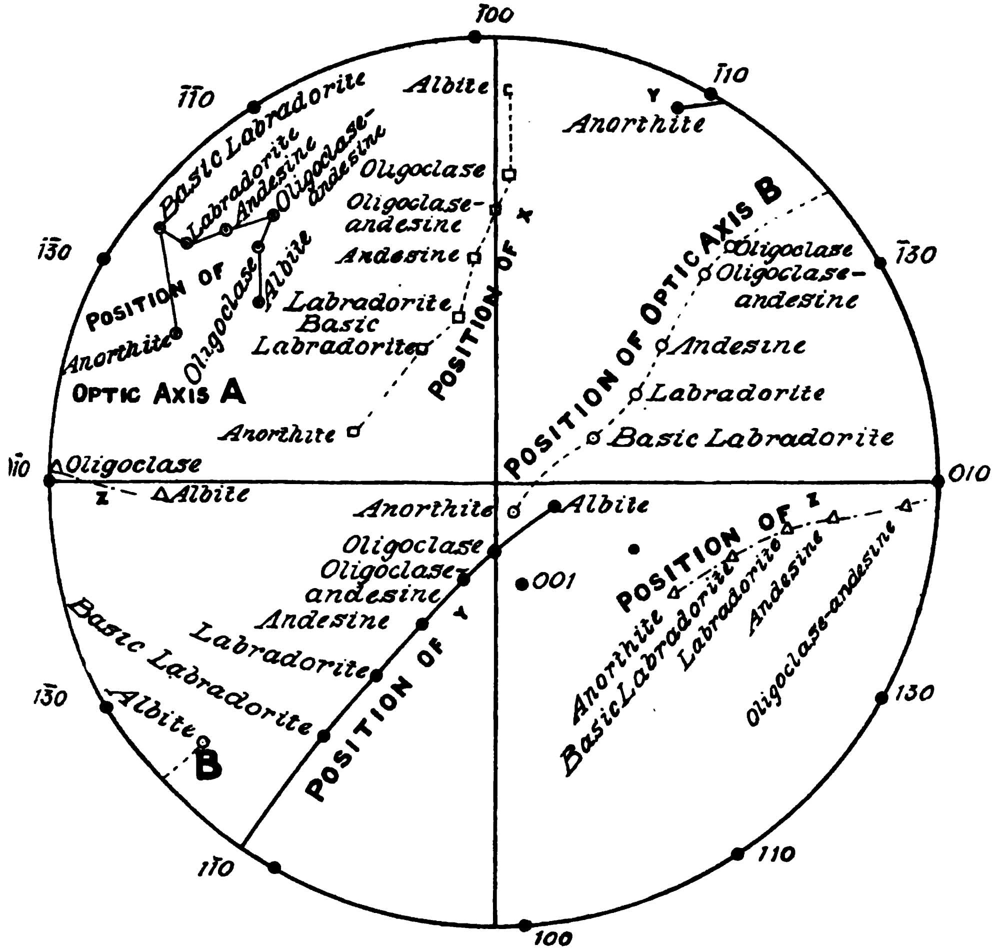


**Fig. 105. Stereographic projection of the optic elements of the plagioclase feldspars on a plane normal to *c*.**

simple crystal form in the various plagioclases is shown in clinographic projection in figures 116-121, 123, 124.

The sign of the acute bisectrix changes three times in the plagioclase series (see table, page 202, and figure 94); the dispersion of the axes is $\rho < v$ about Z from albite to andesine, and $\rho > v$ from labradorite to anorthite, with varying inclined, horizontal or crossed dispersion in the various types, at least two kinds of dispersion being shown by each type.

The indices of refraction increase with the increasing percentage of lime; the birefringence decreases from albite

(0.009) to andesine (0.0065) and then increases to anorthite (0.0130). See page 201 and figure 94.

DIAG. (a). *Sections perpendicular to the axis Y.*

M. de Federov has studied the extinctions in sections perpendicular to the axis Y. They present the highest colors between crossed nicols, and a somewhat characteristic figure in convergent light (p. 87).

As shown by a general épures of Michel Lévy (figures 109-115) and the tabulation below, they vary from albite to andesine inclusive, from +2° to —3°. They are not therefore sufficiently characteristic to separate the acid andesines from the albites. The basic feldspars, on the contrary, ranging from —3° (andesine $Ab_3An_2$) to —10° for labradorite, and to —36° for anorthite, are susceptible of distinction in these sections. It appears, therefore, that very diverse methods succeed in this basic series and generally fail in the acid series. Still the sections of maximum birefringence are capable of rendering service, especially in the absence of twinning.

(b) *Sections perpendicular to the optic axes.*

M. de Federov has also given the extinction angles on the optic axes in simple crystals (1); and to these Michel Lévy has added those of twinned crystals, both those of the Carlsbad type and those of the albite. The numerals (1) and (1′) are made to represent the two individuals of the albite twinned crystals, and (2), (2′) the two adjacent albite individuals of a Carlsbad twinned crystal. It is evident that the parts (1), (1′) may belong to one or the other of the parts (2), (2′). These extinction angles for each optic axis are given in the tabulation below.

*Extinction angles in section normal to A, B, or Y in plagioclase feldspars.*

| Name | Approx. Comp. | Section ⊥A(1) | (1′) | (2) | (2′) | Section ⊥ B(1) | (1′) | (2) | (2′) | Section ⊥ Y |
|---|---|---|---|---|---|---|---|---|---|---|
| **Albite** | **Ab** | +62° | +37° | +30° | +28° | +63° | +40° | +45° | —32° | + 2° |
| **Oligoclase** | **$Ab_4An_1$** | 90° | 0° | +25° | +25° | 90° | 90° | —35° | —25° | + ½° |
| **Oligoclase-andesine** | **$Ab_3An_1$** | – 82° | —40° | +22° | +22° | —82° | —42° | —17° | —16° | 0° |
| **Andesine** | **$Ab_3An_2$** | —71° | —48° | +15° | +35° | —69° | —31° | — 6° | 0° | — 3° |
| **Labradorite** | **$Ab_1An_1$** | —49° | —40° | +10° | +27° | —57° | —23° | + 3° | +14° | —10° |
| **Anorthite** | **An** | —20° | —53° | —25° | +15° | —62° | —12° | +47° | —56° | — 36° |
| | | **Albite twin** | | **Albite twin** | | **Albite twin** | | **Albite twin** | | |
| | | **Carlsbad twin** | | | | **Carlsbad twin** | | | | |

*A* and *B* in the above table designate the two optic axes.

The angles given in the first, second, fifth, and sixth columns [*i. e.*, $\perp A$ (1), and (1′), $\perp B$ (1) and (1′)] refer to the extinction as measured from the trace of the optic plane.

(c) *Sections parallel to the brachypinacoid* 010.

In random rock sections those grains or crystals of feldspars which are cut parallel to 010 have certain properties which permit their identification in many cases. Extinction angles in such sections are very characteristic throughout the plagioclase series and the identification of such sections becomes a matter of importance. Since they are parallel to 010 they can exhibit only one cleavage, the basal. Further, such sections cannot show the albite twinning lamellæ since they are parallel to the albite composition face. In a thin section 0.02 mm. in thickness, if the section is only approximately parallel to 010 so that two albite lamellæ overlap through a distance of 0.3 mm., the section varies less than 4° from strict parallelism, and may be used by allowing for an error of about ±2° in the results. Sections parallel to 010 are also parallel to the composition face of the Carlsbad twins, but in this case the junction of the twins is usually not a plane; there is an irregular interpenetration, and therefore sections rigorously parallel to 010 very often show two individuals of Carlsbad twinning in contact along an irregular line and partly superposed. The basal cleavages in such twins will make an angle of 128° (or 52°). Again, sections parallel to 010 may sometimes be recognized by means of contours of the zones of increment or the external contours. These contours are formed by the following faces, given in the order of their frequence, 001, 201, $\bar{1}01$, 110, $1\bar{1}0$, $20\bar{1}$, and 203. The angles made by these faces in section 010 are shown in figure 106. Sections parallel to 010 are nearly perpendicular to the bisectrix Z in albite, oligoclase, and andesine; in the more basic plagioclases the interference figure departs more and more from the bisectrix Z and approaches the optic axis *A*, but Z is in all the cases the nearest bisectrix. Sections parallel to 010 are nearly perpendicular to the basal cleavage; this cleavage is always near (0°-36°) the negative direction (X′) of extinction, and also near (0°-20°) the composition face of the pericline twinning.

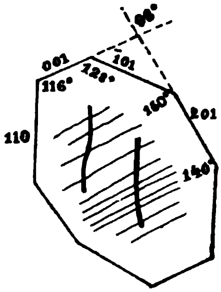


Fig. 106.

Contours of section of feldspar parallel to 010.

Pericline twinning bands are usually much finer than albite twinning bands, and are not as abundant in most cases.

When the position of the basal cleavage and some face of the vertical zone (as 110) can be determined the sign of the extinction angle is given by the rule that positive extinction angles occur in the obtuse angle $\beta$ and negative in the acute angle $\beta$. The sign of the extinction angle can also be determined when the section parallel to 010 is cut so as to show two parts of a Carlsbad twin. In such a case

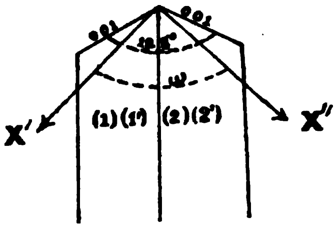


Fig. 107. Carlsbad twin visible in 010.

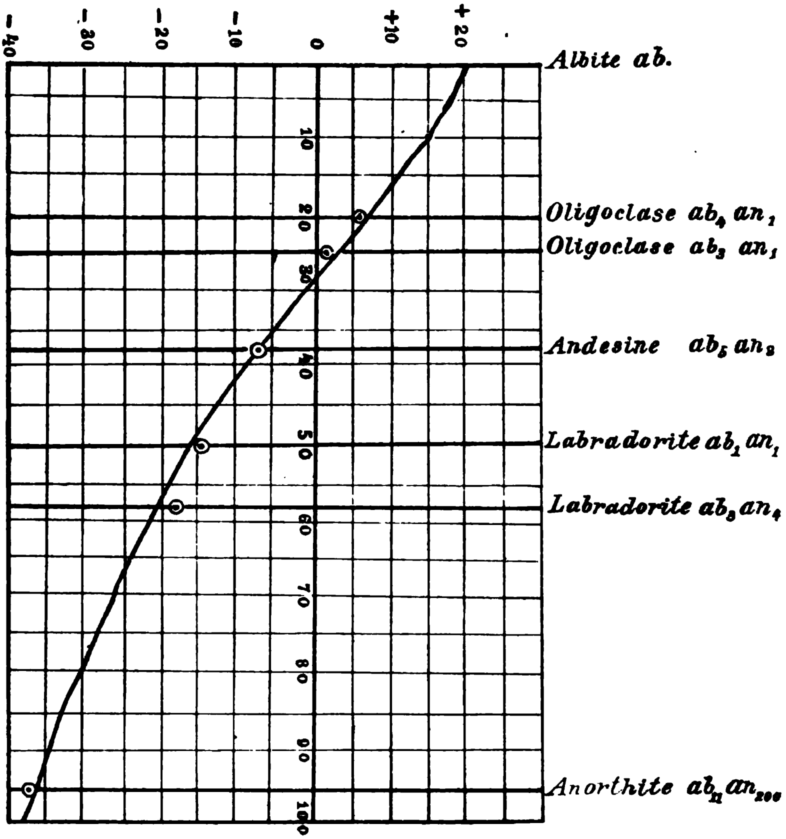


Fig. 108. Extinction angles in sections parallel to 010 in the plagioclase feldspars.

the line bisecting the angle between the basal cleavages in the two parts should also bisect the angle between the negative directions (X) of extinction in the two parts, as in figure 107. The angle ($\omega$) between these two positions will then determine the sign of the angle of extinction in 010, as follows:—

For albite $\omega = 168^\circ$; extinction in 010 is at $+20^\circ$.
For oligoclase $\omega = 128^\circ$; extinction in 010 is at $0^\circ$.
For andesine $\omega = 112^\circ$; extinction in 010 is at $-8^\circ$.
For labradorite $\omega = 96^\circ$; extinction in 010 is at $-16^\circ$.
For anorthite $\omega = 54^\circ$; extinction in 010 is at $-37^\circ$.

The extinction angles of the plagioclase feldspars in sections parallel to 010 are shown graphically in figure 108.

In certain rare cases the albite twinning is absent, while the pericline twinning is well developed. Since it is difficult to recognize such cases it is very fortunate that they are quite uncommon. Extinction angles measured on the trace of the pericline twinning[1] may be tabulated as follows:—

*Extinction angles on the pericline twinning in plagioclase feldspars.*

| Name | Section ⊥Z(1) | (1′) | Section ⊥Y(1) | (1′) | Section ⊥X(1) | (1′) | Section ⊥A(1) | (1′) | Section ⊥B(1) | (1) |
|---|---|---|---|---|---|---|---|---|---|---|
| Albite | — 3° | — 1° | —13° | —16.5° | +77° | —76° | + 5.5° | +41° | —10.5° | —35.5° |
| Oligoclase | — 3° | — 3.5° |  | —27° | —86.5° | +89.5° | — 4.5° | —61° | 0° | +30° |
| Oligoclase-andesine | —4.5° | — 4° |  |  | — 75.5° | +85° | —10.5° | —43.5° | 4° | +49.5° |
| Andesine | — 7° | — 0° | —16° |  | —66.5° | +67° | —21° | — 33° | +12.5° | +42.5° |
| Labradorite | — 8° | + 7.5° | —12° | — 34° | —57.5° | +57° | —25.5° | — 23.5° | +19.5° | +66° |
| Basic labradorite | +17.5° | +12° | —20° | 68° | —49.5° | +42° | —38° | —17° | +15.5° | +49.5° |
| Anorthite | —33.5° | +19.5° | —24.5° | +76.5° | —34.5° | +21° | —57° | —17° | —35° | +13° |
|  | Pericline twin |  | Pericline twin |  | Pericline twin |  | Pericline twin |  | Pericline twin |  |

The angle made in 010 with the trace of 001 by the composition face (or rhombic section—see p. 194) of this twinning is shown in figure 87.

Michel Lévy has platted the optical properties of the various plagioclase feldspars in a series of ingenious and valuable stereographic projections. They are reproduced in figures 109-115. These projections not only show the extinction angle of any section whose orientation is known, but also show the complete range of extinction angles in practically any zone. Thus, the extinction angles in the zone normal to 010 (= maximum equal extinction) are to be found along the vertical diameter in each case. Again, the extinction angles of the vertical zone are given along the circumference of the circle. The extinction angles of any other zone whose axis is in 010 are given along the various meridians and parallels.

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[1] *Comptes Rendus.* 1901. CXXXIII. p. 60.

In stereographic projections, as explained on page 25 the pole of any face is located by a double projection, first upon the surface of an enclosing sphere along a radius, and second upon the equatorial plane of the sphere along lines leading to the south pole. The equatorial plane of projection is commonly (as in this case) chosen as the plane normal to the prismatic zone. The poles of the prism faces are therefore found in the circumference of the plane of projection. The pole of the base is not far from the center, in the lower right hand quadrant. The poles of some other crystal faces are also expressed. The entire surface is divided by meridians and parallels into quadrangular areas having arcs of five degrees. The meridians running from right to left all pass through the poles 010 and 0$\bar{1}$0. The parallels which surround the poles are the various stereographic projections of planes inclined to 010 at intervals of 5°; but in the zone whose axis is normal to *c* and parallel to 010. The trace of the optic plane is shown by the heavy black line passing through the loci of the optic axes *A* and *B* and the bisectrices X and Z. The other heavy lines show the planes connecting Y with the bisectrices. About the axes X, Y, Z are double curves in broken lines. These unite the poles of sections having the same birefringence. About the optic axes the first curve shows the birefringence 0.0025. Then come the curves 0.0035 to 0.0085. The last surrounds the optic normal Y. At the principal intersections of the meridians and parallels are figures which give in degrees the angles of extinction for sections parallel to planes whose poles are at those intersections. These extinction angles vary from 0° to 90°, since they are measured in all cases to the trace of the optic plane. The sign of these angles is determined by Schuster's rule (see page 196).

The fine dotted lines unite poles of sections giving the same extinction angles. The curves composed of crosses separate the negative from the positive extinctions, and coincide with the curves of 0° extinction.

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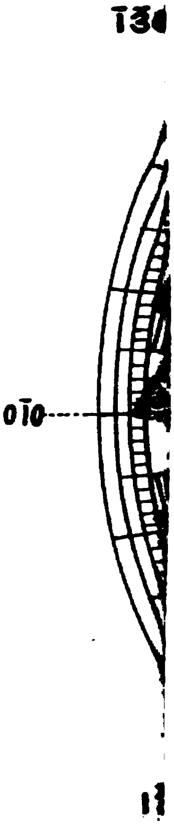
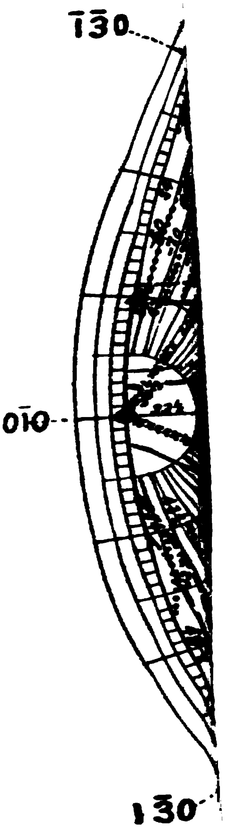
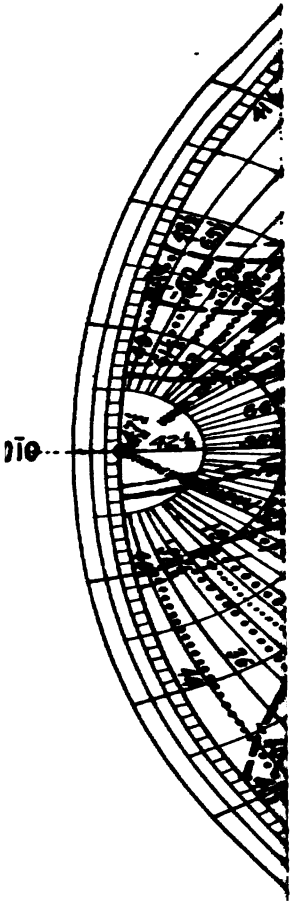
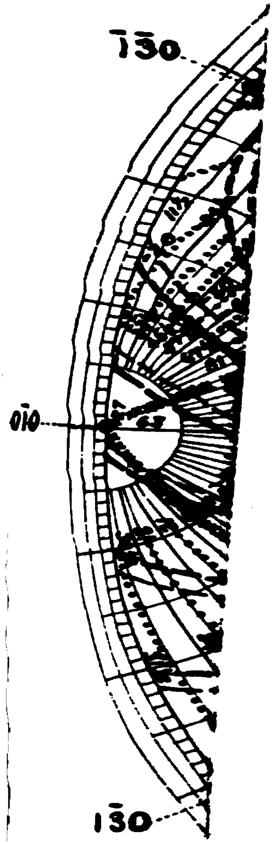

1̄3
01̄0


1̄30
01̄0
13̄0

010




1̄3̄0
010
13̄0

The various planes of a zone whose axis is in 010 and oblique to *c* have their poles on a meridian extending between the poles 010 and 0$\bar{1}$0. The numbers that are seen along this meridian express the extinction angles for the different planes of such a zone. The greater the inclination of the zonal axis the greater the separation of its meridian from the horizontal diameter of the projection.

Day and Allen[1] have recently contributed important evidence that the plagioclase feldspars are actually isomorphous mixtures of two end compounds, albite and anorthite. It is also shown that they are solid solutions, and that the components are miscible in all proportions in both the solid and liquid phases. These conclusions have been reached by means of careful study of the fusing points and specific gravities of the minerals.

There is some difference in practice as to the exact nomenclature of the plagioclases. The following table shows the nomenclature adopted (which is that of Lacroix, with the single exception that A[illegible] is called basic labradorite as is done

| $\frac{Ab_n}{An_m}$ | % An m = | Theoretical C | | | | | | $\frac{Ab_n}{An_m}$ |
|---|---|---|---|---|---|---|---|---|
| | | SiO$_2$ | Al$_2$O$_3$ | C | Fouqué 1894 | Lacroix 1896 | | |
| 1:0 | .0.0 | 68.7 | 19.5 | | Albite | Albite | | 1:0 |
| 12:1 | 7.7 | 66.6 | 20.9 | | | Oligoclase | Olig.-albite | 12:1 |
| 8:1 | 11.1 | 65.7 | 21.6 | | lig.-alb. | | | 8:1 |
| 6:1 | 14.3 | 64.9 | 22.1 | | | | | 6:1 |
| 4:1 | 20.0 | 63.3 | 23.1 | | ligoclase | | Oligoclase | 4:1 |
| 3:1 | 25.0 | 62.0 | 24.0 | | lig.-and. | | Olig.-and. | 3:1 |
| 2:1 | 33.3 | 59.9 | 25.4 | | | Andesine | And.-olig. | 2:1 |
| 3:2 | 40.0 | 58.1 | 26.6 | | ndesine | | Andesine | 3:2 |
| 4:3 | 42.9 | 57.4 | 27.1 | | | | | 4:3 |
| 1:1 | 50.0 | 55.6 | 28.3 | 1 | abrador. | Labradorite | Labradorite | 1:1 |
| 3:4 | 57.1 | 53.7 | 29.6 | 1 | | | Labr.-byt. | 3:4 |
| 2:3 | 60.0 | 53.0 | 30.1 | 1 | abr.-byt. | | | 2:3 |
| 1:2 | 66.7 | 51.4 | 31.2 | 1 | | | | 1:2 |
| 1:3 | 75.0 | 49.3 | 32.6 | 1 | ytownite | Bytownite | Bytownite | 1:3 |
| 1:4 | 80.0 | 48.0 | 33.4 | 1 | | | | 1:4 |
| 1:6 | 85.7 | 46.6 | 34.4 | 1 | | | Byt.-anor. | 1:6 |
| 1:8 | 88.9 | 45.9 | 34.9 | 1 | | | | 1:8 |
| 0:1 | 100.0 | 43.2 | 36.7 | 2 | northite | Anorthite | | 0:1 |

[1] Determined by graphic

[2] In part determined by . 93.

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## ALBITE.

TRICLINIC $a : b : c :: 0.6333 : 1 : 0.5572$ $NaAlSi_3O_8$

$\alpha = 94° 3'$ $\beta = 116° 27'$ $\gamma = 88° 9'$

PHYS. CHAR. Crystals show the form and habits common to the feldspar group. They are often tabular || 010, sometimes elongated || *c*, and sometimes parallel to intersection of 010 and 101. When pericline twinning is present the crystals are often elongated || *b*, or tabular || $\bar{1}01$. Also found in lamellar or granular masses. Cleavage perfect || 001, somewhat imperfect || 010, imperfect || 110. Fracture uneven or conchoidal. Twinning of the albite type nearly always present; this may be combined with other types especially the Carlsbad or pericline. Baveno and Manebach twinning uncommon. Esterel twinning, in which the twinning axis is the axis *a* and the composition face is the base, occurs rarely. Roc Tourné twinning is a type common in the metamorphosed limestones. It consists of two groups of crystals, each twinned on the albite law, which are again twinned as groups according to the same law. These groups interpenetrate in such a way that their composition faces, if one were present, would be a plane parallel to *c* and normal to 010. H. = 6.-6.5. G. = 2.62 to 2.63 (2.6 artificial crystals). Insoluble. Fusible at 4.

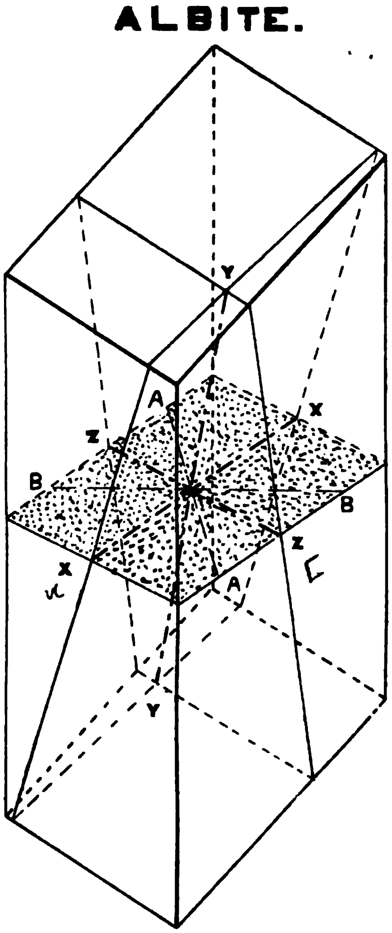


Fig. 116. Optical orientation of albite (Ab). Crystal limited by 001, 010, and 100. The dotted plane is the optic plane.

OPT. PROP. A plane perpendicular to the acute bisectrix makes an angle of 101° to 102° with 001 and cuts the acute angle between 001 and 010. The acute bisectrix makes an angle of 15° with a normal to 010. The extinction angle in 010 is +20° to +21°; in 001 it is +3° to +4°. The extinction angle in a section normal to Z is 20°, and in a section normal to X it is 74° when measured to the optic plane. The maximum angle of equal extinction in the zone normal to 010 is —16°. Other extinction angles are given in preceding tables. The acute bisectrix is positive. In sections normal to Z the acute bisectrix, the dispersion of the optic axes is $\rho < v$, distinct in one axis, indistinct in the other. In the same sections there is very weak horizontal dispersion combined with strong dispersion of the bisectrices.

$$+2V = 77^\circ$$

$n_g = 1.540$ Na (ML and Lx) $= 1.5331$ Na (Zimanyi)
$n_m = 1.534$ Na (ML and Lx) $= 1.5287$ Na (Zimanyi)
$n_p = 1.532$ Na (ML and Lx) $= 1.5392$ Na (Zimanyi)
$n_g - n_p = 0.009$ (direct measure, ML and Lx)

Color white, bluish, gray, reddish, greenish; sometimes opalescent on 001. Luster vitreous. Colorless in thin section.

ALTER. The modes and products of alteration of albite are those common to the group.

OCCUR. Albite is found in many crystalline rocks, but is rare as a primary constituent of igneous rocks. It is formed by the alteration of analcite, and also by the metamorphism of other feldspars in the process of saussuritization. It is often an abundant constituent of crystalline schists. It forms an important part of many veins, both metalliferous and non-metalliferous, where it has been formed by hydrothermal action. Finally it occurs occasionally in sedimentary limestones.

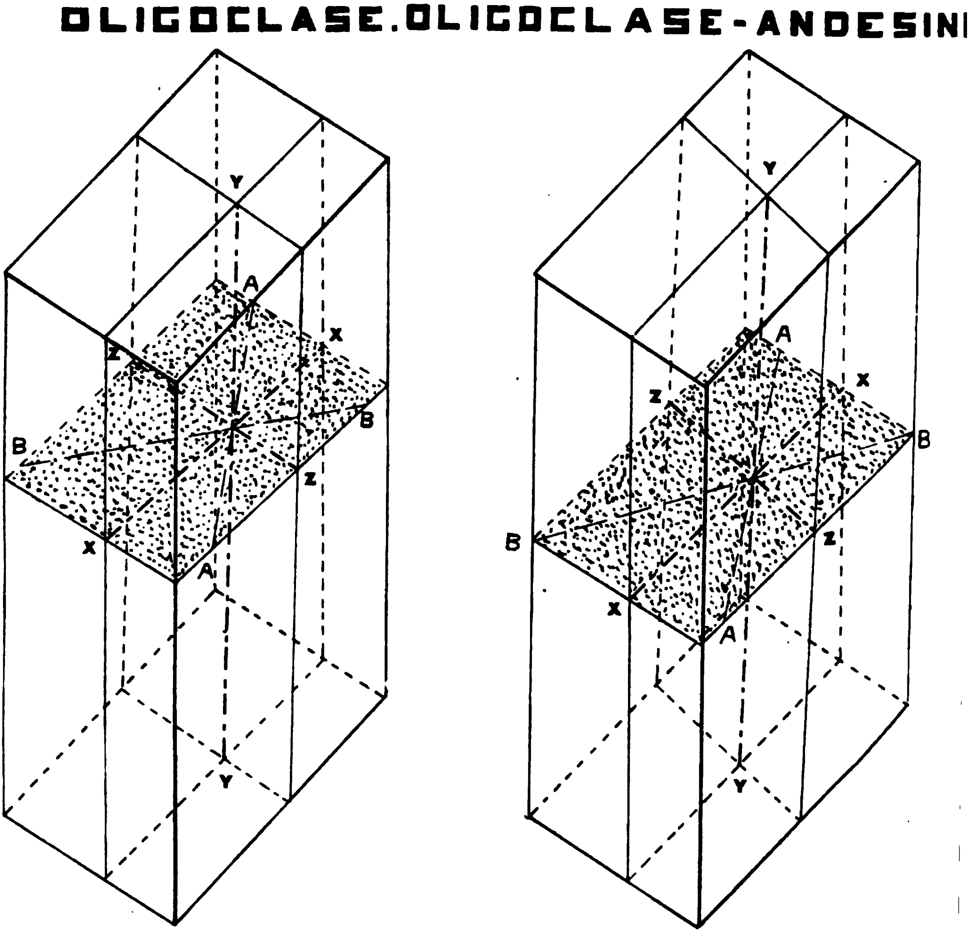
DIAG. Distinguished from preceding feldspars by presence of albite (and sometimes pericline) twinning, and absence of the quadrille structure of microcline. Differs from the other plagioclase feldspars in specific gravity and optic properties as shown in the preceding tables.

## OLIGOCLASE.

TRICLINIC $a:b:c::0.6321:1:0.5524$ Ab$_{12}$An$_1$ to Ab$_3$An$_1$
$\alpha = 93° 4' \ \beta = 116° 22' \ \gamma = 90° 4'$

PHYS. CHAR. Crystals uncommon; usually in lamellar or compact masses. Microscopic twinning according to albite, pericline, and Carlsbad laws. Cleavage perfect || 001, less perfect || 010, imperfect || 110. H. = 6. G. = 2.635 to 2.67 (2.61 to 2.64 artificial crystals). Fusible at 3.5. Insoluble.

OPT. PROP. The axis Z makes an angle of 1° to 6° with a normal to 010, and an angle of 80° to 94° with a normal to 001. The axis X makes an angle of 91° to 96° with a normal to 001.



Figs. 117, 118. Optical orientation of oligoclase (Ab$_4$An$_1$) and oligoclase—andesine (Ab$_2$An$_1$). Crystal limited by 001, 010, and 100. The dotted plane is the optic plane.

and an angle of 75° to 90° with a normal to 010. The extinction angle in 001 is 0° to +2.5°, and in 010 is 0° to +15°. The extinction angle referred to the optic plane in a section normal to Z is 3° to 15°, and in a section normal to X is 75° to 88°. The maximum angle of equal extinction in the zone normal to 010 is —10° to +7°. Other extinction angles, and the relation of these to the composition, are given in preceding tables. The acute bisectrix of the acid oligoclases is positive, and of the basic types is negative. In sections normal to Z the dispersion of the optic axes is distinct with $\rho < v$, while there is crossed dispersion, distinct on one side and indistinct on the other, combined with inclined dispersion of the bisectrices.

$(\pm)\ 2V = 80°$ to $90°$

| | $Ab_6An_1$ | $Ab_4An_1$ | $Ab_3An_1$ |
|---|---|---|---|
| $n_g =$ | 1.5457 | 1.5469 | 1.5490 |
| $n_m =$ | 1.5415 | 1.5431 | 1.5458 |
| $n_p =$ | 1.5373 | 1.5389 | 1.5417 |
| $n_g - n_p =$ | 0.0084 | 0.0080 | 0.0073 |

Color white, grayish, greenish, reddish, sometimes with internal fire-like reflections. Luster vitreous. Colorless in thin section.

ALTER. Similar to albite, but kaolinization is less frequent than in albite.

OCCUR. Oligoclase occurs in eruptive rocks and in crystalline schists. Oligoclase-andesine is more abundant and wide spread in occurrence than the other varieties.

DIAG. See the preceding tables.

## ANDESINE.

TRICLINIC $a:b:c::0.6356:1:0.5521$ $Ab_2An_1$ to $Ab_4An_3$

$\alpha = 93° 23'$ $\beta = 116° 29'$ $\gamma = 89° 59'$

PHYS. CHAR. Crystals rare; usually massive. Twins according to the Carlsbad, Baveno, albite, pericline, and Esterel laws. Pericline twinning visible only microscopically. Albite twinning bands often too narrow to be visible macroscopically. Cleavage perfect || 001, less perfect || 010, sometimes found in traces || 110. H. = 5. to 6. G. = 2.671 to 2.684 (2.658 to 2.674 artificial crystals). Nearly insoluble in acids. Fusible in thin splinters only.

OPT. PROP. A plane perpendicular to the acute bisectrix makes an angle of 100° to 112° with 001, and 174° to 163° with

010. The extinction angle in 001 is —2° to —2.5°, and in 010 it is —4° to —10°, while the maximum angle of equal extinction in the zone normal to 010 is +16° to +25°. Other extinction angles and the relation of these to the varying composition are given in the preceding tables. The acute bisectrix is positive. In sections normal to Z the axial dispersion is $\rho < v$ with distinct horizontal and weak inclined dispersion of the bisectrices.

$$(+)\ 2V = 87° \text{ to } 90°$$
$$n_g = 1.556$$
$$n_m = 1.553$$
$$n_p = 1.549$$
$$n_g - n_p = 0.007$$

Color white, gray, greenish, yellowish, red. Luster vitreous. Colorless in thin section.

Alter. Similar to the alteration of oligoclase.

Occur. Andesine is abundant in igneous rocks, both plutonic and volcanic; it occurs in gneisses and schists, also, rarely, in veins.

**ANDESINE.**

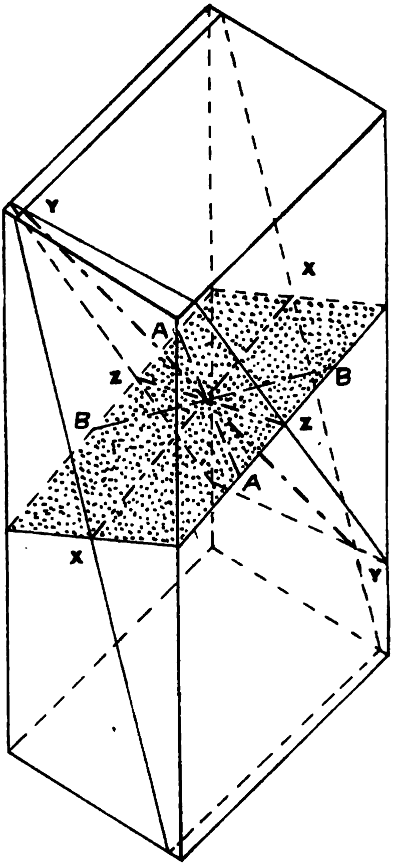


Fig. 119. Optical orientation of andesine ($Ab_3An_2$). Crystal limited by 001, 010, and 100. The dotted plane is the optic plane.

Diag. See the preceding tables.

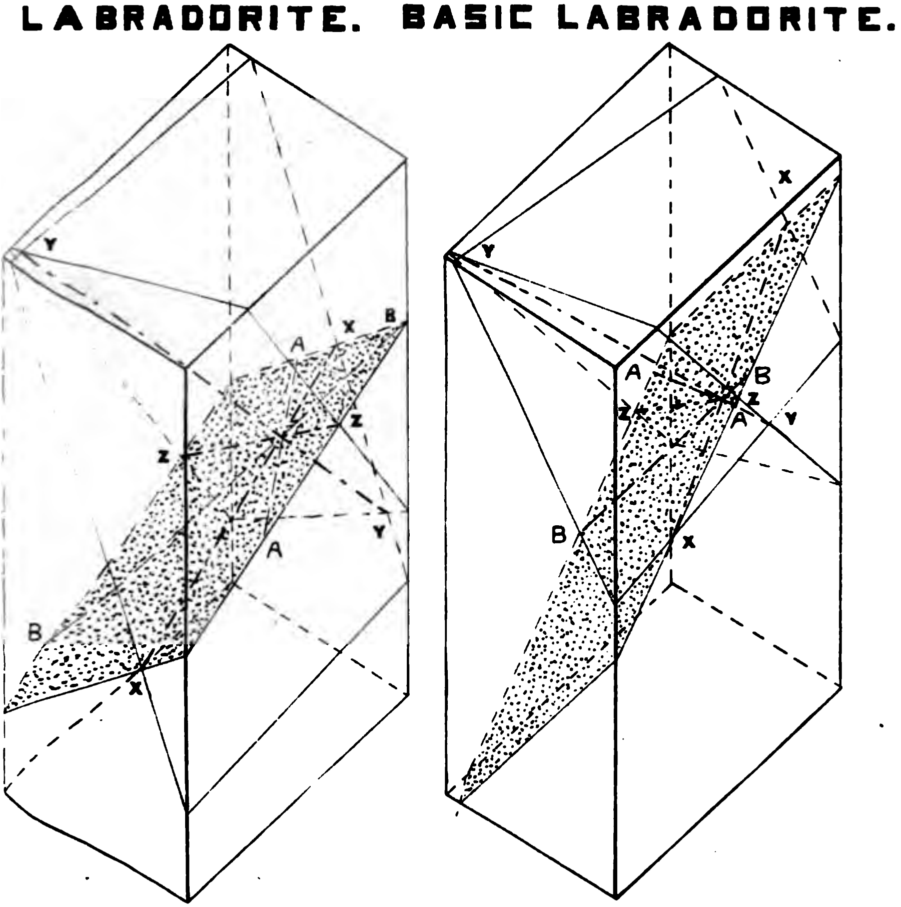
### LABRADORITE.

Triclinic $a:b:c::0.6377:1:0.5547$ $Ab_1An_1$ to $Ab_1An_2$

$\alpha = 93° 31'$ $\beta = 116° 3'$ $\gamma = 89° 54'$

Phys. Char. Crystals often tabular || 010; also massive, cleavable; granular, or cryptocrystalline. Twinning nearly always present of the Carlsbad, albite, pericline, Baveno, or Manebach type; the first two or even three are often present together. Cleavage perfect || 001, less perfect || 010, sometimes imperfect || 1 10 and some other prisms. H. = 5. to 6. G. = 2.694 to 2.716 (2.685 to 2.711 artificial crystals). Only slightly soluble in boiling HCl. Fusible at 3. to a colorless glass.

Opt. Prop. A plane perpendicular to the acute bisectrix makes an angle of 122° to 130° with 001, and 152° to 143°



**Figs. 120, 121.** Optical orientation of labradorite ($Ab_1An_1$) and basic labradorite ($Ab_3An_4$). Crystal limited by 001, 010, and 100. The dotted plane is the optic plane.

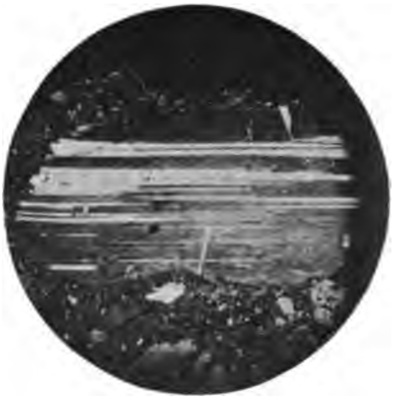


Fig. 122. Section of labradorite showing Carlsbad, albite, and pericline twinning in anamesite from near Frankfort-am-Main. H. 537.1 + nicols. × 20.

with 010. The extinction angle in 001 is —5.5° to —11°, and in 010 it is —20° to —25°, while the maximum angle of equal extinction in the zone normal to 010 is +34° to +37°. Other extinction angles and the relation of these to the varying chemical composition are given in the preceding tables. The acute bisectrix is positive. In sections normal to Z, the acute bisectrix, the dispersion of the optic axes is $\rho > v$, with distinct crossed dispersion and weak inclined dispersion of the bisectrices.

$$+\ 2V = 77° \text{ to } 80°$$

| $n_g =$ | $Ab_1An_1$ | $Ab_3An_4$ |
|---|---|---|
| $n_g =$ | 1.5625 | 1.5689 |
| $n_m =$ | 1.5578 | 1.5639 |
| $n_p =$ | 1.5548 | 1.5611 |
| $n_g - n_p =$ | 0.0077 | 0.0078 |

Color gray, greenish, brown, colorless, white; often exhibits play of colors especially on 010. Luster vitreous. Colorless in thin section.

Incl. The colored varieties contain abundant inclusions of hematite or ilmenite, or, in other cases, black acicular inclusions regularly arranged. In all varieties tiny inclusions of augite, amphibole, or magnetite are common, as well as liquid inclusions.

Alter. The alteration of labradorite often results in the formation of a micaceous mass; at other times it yields dipyre or hydrargillite; this mineral alters under some conditions to an aggregate—called saussurite—composed of zoisite, epidote, albite, often with some tremolite, and sometimes garnet, rutile, quartz, etc.

Occur. Labradorite is a common constituent of many basic igneous rocks, and occasionally is so abundant as to form a rock by itself (plagioclasite or anorthosite). It is also found in rocks produced by regional as well as contact metamorphism. Finally, it occurs sparingly in meteorites.

DIAG. See the preceding tables.

## BYTOWNITE.

TRICLINIC Axial ratio unknown $Ab_1An_3$ to $Ab_1An_3$

PHYS. CHAR. Crystals very rare; usually in microscopic lamellæ or masses either granular or cleavable. Twinning occurs according to the albite, Carlsbad, Baveno, and pericline laws. Cleavage perfect || 001, less perfect || 010. Colorless, white, or tinted. H. = 6. G. = 2.728 to 2.747 (2.725 to 2.747 artificial crystals). Fusible to a colorless glass. Slowly soluble in acids leaving a residue of gelatinous silica.

OPT. PROP. The extinction angle in 001 is about —18°, and in 010 it is about —33°. The extinction referred to the optic plane in a section normal to Z is about 42°, and in a section normal to X it is about 57°. The maximum angle of equal extinction in the zone normal to 010 is about + 43°. The acute bisectrix is negative except in the most acid varieties ($Ab_1An_3$) in which it is positive. The optic angle is sensibly 90° in the variety $Ab_1An_4$. In sections normal to Z the dispersion of the optic axes is $\rho > v$, with weak inclined and crossed dispersion of the bisectrices.

$(\pm)\ 2V = 80°$ to $90°$

| | $Ab_1An_3$ | $Ab_1An_4$ | $Ab_1An_6$ |
|---|---|---|---|
| $n_g$[1] = | 1.578 | 1.581 | 1.583 |
| $n_m$ = | 1.573 | 1.5765 | 1.579 |
| $n_p$ = | 1.569 | 1.572 | 1.574 |
| $n_g - n_p$ = | 0.009 | 0.009 | 0.009 |

Color greenish, white, gray, colorless. Luster vitreous. Colorless in thin section.

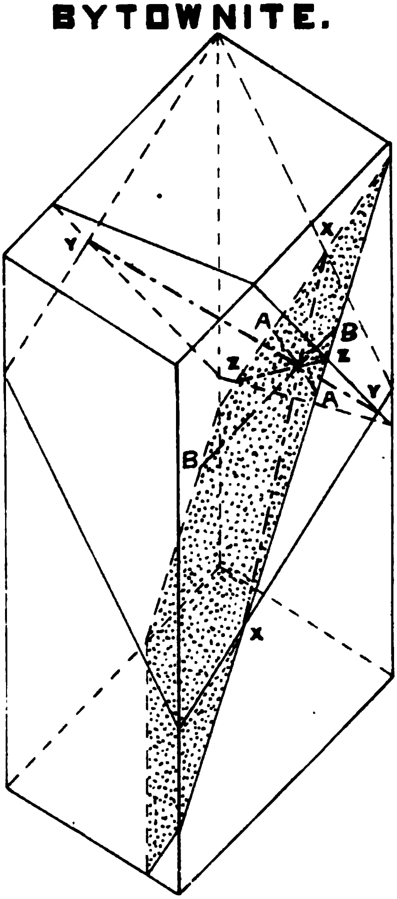


Fig. 123. Optical orientation of bytownite ($Ab_1An_3$). Crystal limited by 001, 010, and 100. The dotted plane is the optic plane.

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[1] Indices of refraction as determined by graphic method. See Michel Lévy · *Determination des Feldspaths.* 1896. Plate XVI.

Alter. Similar to labradorite.

Occur. Bytownite is the rarest of the plagioclase feldspars. It occurs in basic igneous rocks both plutonic and volcanic, often associated with dominant labradorite or anorthite. It is found also in rocks produced by contact and regional metamorphism. Finally, it is common, with anorthite, in some meteorites.

Diag. See the preceding tables.

## ANORTHITE.

Triclinic $a:b:c::0.6342:1:0.5501$ $CaAl_2Si_2O_8$

$\alpha = 93° 13' \ \beta = 115° 57' \ \gamma = 91° 13'$

Phys. Char. Crystals usually flattened || 010, sometimes about equidimensional or elongated || *c*, or || *b*. But more commonly massive, either lamellar or, more rarely, granular. Twinning nearly always present of the albite type; Carlsbad, pericline, and Baveno twinning not uncommon, often combined with the first named. Cleavage perfect || 001, less perfect || 010. H. = 6. to 6.5 G. = 2.74 to 2.76 (2.765 artificial crystals). Soluble in HCl with separation of gelatinous silica. Fusible at 5. to a colorless glass.

Opt. Prop. A plane perpendicular to the obtuse bisectrix makes an angle of about 140° with 001, and 133° with 010. The extinction angle in 001 is —37°, and in 010 it is —42°, while the maximum angle of equal extinction in the zone normal to 010 is +56°.

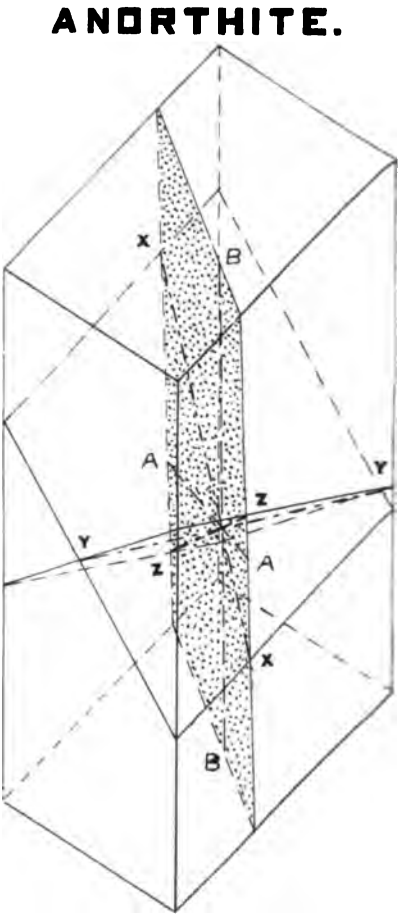

**Fig. 124. Optical orientation of anorthite (An). Crystal limited by 001. 010, and 100. The dotted plane is the optic plane.**

Other extinction angles are given in the preceding tables. The acute bisectrix is negative. In sections normal to Z, the obtuse bisectrix, the dispersion of the optic axes is $\rho > v$, with weak inclined and crossed dispersion of the bisectrices.

$$(+)\ 2V = 75^\circ \text{ to } 80^\circ$$
$$n_g = 1.5884 \quad n_m = 1.5837 \quad n_p = 1.5757$$
$$n_g - n_p = 0.0127$$

Color white, grayish, reddish. Luster vitreous. Colorless in thin section.

ALTER. Anorthite alters to a micaceous mass, to scapolite, to zeolites, to prehnite, to calcite, epidote and quartz, or by metamorphism to saussurite. Finally, it may alter to wollastonite (even completely) under conditions that are not fully understood.

OCCUR. It occurs in basic igneous rocks as an essential constituent, but is not common in isolated crystals. It is also found in rocks produced either by regional or contact metamorphism, and in meteorites.

DIAG. Anorthite, of all the feldspars, has the strongest birefringence and the highest relief. For other means of distinction see the preceding tables.

### FERRINATRITE.

HEXAGONAL $c = 0.553$ $Na_6Fe_2(SO_4)_4 + 6H_2O$

PHYS. CHAR. Crystals acicular, rare; usually lamellar radiated in spherical forms. Cleavage perfect || 10$\bar{1}$0, imperfect || 11$\bar{2}$0. H. = 2. G. = 2.56.

OPT. CHAR. Uniaxial and positive. Refringence moderate, birefringence strong. Color pale greenish, pale grayish, white; colorless in thin section; $n_g = 1.613$, $n_p = 1.558$; $n_g - n_p = 0.055$.

OCCUR. Found with other sulphates. Very rare.

### FISCHERITE.

ORTHORHOMBIC $a:b:c::0.594:1:?$ $AlPO_4 \cdot Al(OH)_3$

PHYS. CHAR. Crystals small, prismatic to acicular; scales. H. = 5. G. = 2.46. Gives $H_2O$ B.B. Soluble in $H_2SO_4$.

OPT. PROP. The optic plane is parallel to 100; the bisectrix Z is normal to 001. Axial optic angle large. Color green.

$$(+)\ 2E = 106^\circ\ 18'\ \text{Na}\ (2V = 61^\circ\ 51'\ \text{Na})$$
$$n_m = 1.555$$

OCCUR. Found in veins in slate, etc. Very rare.

### FLINKITE.

ORTHORHOMBIC $a:b:c::0.413:1:0.739$ $MnAsO_4 \cdot 2Mn(OH)_2$

PHYS. CHAR. Crystals minute. tabular || 001; in feathery aggregates. H. $= 4.-4.5$. G. $= 3.87$. Fuses easily. Readily soluble in acids.

OPT. PROP. The optic plane is parallel to 001; the bisectrix Z is normal to 100. Axial optic angle large; dispersion probably $\rho < v$. Color greenish brown. Pleochroism distinct. Z = orange brown, Y = yellowish green, X = yellowish to brownish green.

OCCUR. Found in iron-manganese mines in Sweden. Very rare.

**Sarkinite** [$Mn_3(AsO_4)_2 \cdot Mn(OH)_2$] is chemically related to flinkite. It is monoclinic with $a:b:c::2.002:1:1.515$, and $\beta = 62° \, 13'$. H. $= 4.-5$. G. $= 4.18$. Fuses at about 4. Easily soluble in HCl. Optic plane parallel to 010; $X \wedge c = -54°$. Optic angle about 83° about X. Birefringence strong. Color rose red, reddish yellow. Found with flinkite. Very rare.

**Allactite** [$Mn_3(AsO_4)_2 \cdot Mn(OH)_2$] is another monoclinic basic arsenate of manganese, with $a:b:c::0.613:1:0.334$ and $\beta = 84° \, 17'$. Crystals small prismatic. Cleavage distinct || 101, indistinct || 100. H. $= 4.5$. G. $= 3.84$. Nearly infusible. Easily soluble. Optic plane normal to 010. Optic angle small; dispersion extraordinary. $2H = 12° \, 22'$ Li, $2H = 9° \, 12'$ Na, $2H = 0°$ Tl, $2H = 11° \, 36'$ $CuSO_4$. The bisectrix is in 010 for red and yellow, and normal to 010 for blue. $X \wedge c = -49° \, 12'$ for red and yellow. Optically —. Birefringence strong; $n_m = 1.778$ Li. $n_m = 1.786$ Na. Color brownish red; streak brownish gray. Strongly pleochroic, hyacinth red to olive green. Found in druses in dolomite. Very rare.

**Synadelphite** [$2(Al,Mn)AsO_4 \cdot 5Mn(OH)_2$] is a basic arsenate of manganese and aluminum. It is monoclinic, with $a:b:c::0.858:1:0.919$, and $\beta = 90°$. Crystals prismatic or pyramidal. Also granular. H. $= 4.5$. G. $= 3.47$. Fuses easily. Readily soluble in acids. Optic plane normal to 010 and inclined 45° to $c$; acute bisectrix Z normal to 010. Optic angle small. Color brownish black to black. Feebly pleochroic in dark brown colors. Found with preceding minerals and barite. Very rare.

**Hematolite** [$(Al,Mn)AsO_4 \cdot 4Mn(OH)_2$] is related to synadelphite, both in composition and physical characters. It is apparently rhombohedral, with $c = 0.888$, but on optical grounds it has been referred to the monoclinic or triclinic system. Crystals rhombohedral. Cleavage perfect || 0001. H. $= 3.5$. G. $= 3.35$. Infusible. Readily soluble. Optically negative and uniaxial; often biaxial with small optic angle; $n_g = 1.723$ (red), $n_g = 1.740$ (blue). Color brownish red, garnet red; yellow to brown in thin section. Found in cavities in dolomite in Sweden. Very rare.

## FLUELLITE.

ORTHORHOMBIC $a:b:c::0.77:1:1.88$ $AlF_3 + H_2O$

PHYS. CHAR. Crystals pyramidal with base. Cleavage indistinct || 111. H. $= 3$. G. $= 2.17$.

Opt. Prop. The optic plane is parallel to 100; the acute bisectrix is normal to 001. $2E = 100° \pm$. $n = 1.47$. Colorless to white. Luster vitreous.

Occur. Found in quartz with wavellite and torbernite. Very rare.

## FLUORITE.

Isometric $CaF_2$

Phys. Char. Crystals usually cubic, sometimes octahedral or dodecahedral. Cubic crystals sometimes grouped in parallel position producing skeleton crystals elongated in the direction of an axis of quaternary or of ternary symmetry. Twinning common with the octahedral face the twinning plane; usually the two individuals interpenetrate. Perfect octahedral cleavage. Transparent or translucent. H. = 4. G. = 3.18. Fusible with red flame color. Soluble in $H_2SO_4$ with evolution of HF.

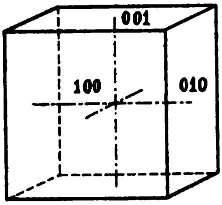

Fig. 125.
A simple crystal form of fluorite.

Opt. Prop. On account of the low index of refraction, the negative relief is marked. Fluorite often shows abnormal birefringence; Hussak describes these crystals as composed of orthorhombic individuals with X perpendicular to the cubic faces. He regards the birefringence as secondary and ascribes it to internal tension; it does not disappear at red heat.

$$n = 1.434.$$

Color often bright; yellow, blue, purple, white, green, red, brown. Streak white. Luster vitreous. The color of fluorite is not uniformly distributed. It is probably often due to small quantities of oxides of iron and manganese; but in certain cases it has been shown to be due to other impurities, notably free fluorine or hydrocarbons.

Occur. Fluorite is rarely found as a primary constituent of igneous rocks; in certain cases it seems to have been formed in igneous rocks through the action of fumaroles. Common in veins associated with quartz and barite, and also in some metalliferous veins. Finally, it is found in sedimentary and metamorphic rocks.

Diag. The crystal form, octahedral cleavage, very low refringence, vitreous luster, softness, and ready fusibility are useful diagnostics. Color, when present, is not uniformly distributed.

**FORSTERITE,** see olivine group. **FOUQUÉITE,** see epidote group. **FRANKLINITE,** see spinel group.

## FRIEDELITE.

RHOMBOHEDRAL $c = 0.562$ $H_7(MnCl)Mn(SiO_4)_4$

PHYS. CHAR. Crystals usually hexagonal tablets. Also massive, cleavable to compact. Cleavage perfect || 0001. H. = 4-5. G. = 3.07. Easily fusible to a black glass. Soluble in HCl.

OPT. PROP. Uniaxial and negative. Birefringence strong. Color rose red. Streak pink. In sections about 0.5 mm. thick pleochroic with Z = dark reddish brown, X = very pale yellow.

OCCUR. Found in manganese mines. Rare.

**Pyrosmalite** $\{ H_7[(Fe,Mn)Cl](Fe,Mn)_4(SiO_4) \}$ is very similar. It occurs in thick prismatic or tabular crystals of rhombohedral symmetry with $c = 0.531$; also massive. Cleavage perfect || 0001, imperfect || 10$\bar{1}$0. G. = 3.06-3.19. Fusible at 2. to a black magnetic glass. Gelatinizes in HCl. Uniaxial and negative with strong birefringence. Refringence, $n = 1.66$. Color blackish green to pale brown, also grayish green. Streak paler. Luster pearly. Found in iron mines of Sweden. Rare.

**GADOLINITE,** see datolite group. **GAHNITE,** see spinel group.

## GALENA.

ISOMETRIC PbS

PHYS. CHAR. Commonly in cubes; less often octahedrons or cubo-octahedrons. Also reticulated, skeletal, rarely stalactitic. Often massive cleavable, coarse or fine. Rarely fibrous. Twinning on 111; less often on 441, 311 or 331. Cleavage perfect || 100. H. = 2.5. G. = 7.5. Fusible and yields lead globule. Decomposed by strong $H_2SO_4$ with formation of lead sulphate.

OPT. PROP. Opaque. Color and streak lead gray. Luster metallic. Refringence high, $n = 3.912$. Polishes readily; upon etching the portion dissolved is often limited by cleavage planes.

ALTER. The commonest alteration product is cerussite, but many others are found, including pyromorphite, mimetite, wulfenite, anglesite, linarite, minium. By partial removal of the lead native sulphur is sometimes left along the cleavages of galena.

OCCUR. Galena is one of the most widely distributed of the metallic sulphides. It is found in quartz veins in rocks of all kinds, often associated with ores of zinc, copper or silver; it is abundant in some calcite (or dolomite) veins, and in disseminated deposits in sedimentary rocks often associated with sphalerite, pyrite, marcasite, and various carbonates. It occurs less commonly as a product of contact metamorphism; as a result of the action of hot springs upon coins; and as a furnace product.

**Argentite** ($Ag_2S$) is isomorphous with galena. Crystals often distorted; also reticulated, filiform, massive, encrusting. Cleavage in traces || 100 and 110. H. = 2.5. G. = 7.3. Sectile. Fusible with intumescence yielding a silver globule. Soluble in $HNO_3$. Opaque. Color and streak blackish lead gray. Luster metallic. By alteration yields native silver. Found chiefly in veins in rocks of all kinds often associated with galena, and other lead ores; also with copper, gold, etc.

DIAG. Galena differs from other sulphides in its perfect cubic cleavage and brilliant luster.

## GANOPHYLLITE.

MONOCLINIC $a:b:c::0.413:1:1.831$ $Mn_7(AlO)_2(SiO_3)_8 + 6H_2O$?

$\beta = 86° 39'$

COMP. According to Hamberg the formula should be written $H_{12}Mn_7Al_2(SiO_4)_8$. Originally described as a manganese zeolite, but Clarke considers it a hydrated manganese phlogopite.

PHYS. CHAR. Crystals short prismatic with 001 and 011. Also foliated, micaceous. Cleavage perfect || 001. Percussion figure on cleavage a six-rayed star with one ray || 010; the others nearly || 110 and $1\bar{1}0$. H. = 4.-4.5. G. = 2.84. Loses water at very low temperature like the zeolites. Soluble in acids.

OPT. PROP. The plane of the optic axes is parallel to 010; the negative acute bisectrix is normal to 001. Refringence high, birefringence strong. Optic angle considerable. Dispersion $\rho < v$.

$$(-)\quad 2E = 41° 53' \text{ Na} \quad 2V = 23° 52' \text{ Na}$$

$$n_g = 1.7298 \quad n_m = 1.7287 \quad n_p = 1.7046$$

$$n_g - n_p = 0.0252$$

Color brown. Luster vitreous, brilliant. Pleochroism distinct in thin section with Z = Y = colorless, X = yellowish brown.

OCCUR. Found in manganese mines in Sweden. Very rare.

## Garnet Group.

PHYS. CHAR. The minerals of the garnet group are especially characterized by their isometric forms, usually dodecahedral, sometimes trapezohedral, or these combined, or modified by the hexactahedron; very rarely octahedrons are found. Twinning is rare. They have no cleavage, but have an irregular fracture. They are often zonal. The color is variable, being red, brown, yellow, white, green, black, the colors often bright. The hardness is about 7. (6.5-7.5). The specific gravity ranges from 3.4. to 4.3.

OPT. PROP. Garnets being isometric are normally and most commonly isotropic, but many samples show anomalous double refraction. This fact has called forth several elaborate studies of the anomaly, but its cause is not yet fully determined. Klein argues that the anisotropic character is not dependent upon the chemical composition, but apparently upon the external form, and he therefore considers it of secondary origin, perhaps due to internal strains. Mallard, on the other hand, urges that the optical constants in a given type are constant in all specimens, and concludes that the mineral must therefore be truly not isometric, but apparently orthorhombic, the exterior isometric form being produced by twinning.

In all garnets having birefringence the crystal may be considered to be made up of a number of similar pyramids whose vertices meet at the center of the crystal. Some garnets may be mechanically separated into parts corresponding to these pyramids.

Several types may be distinguished, as follows:—

1. Dodecahedral or pyreneite type. In this type the exterior form is a dodecahedron, which is made up of twelve rhombic pyramids whose bases form the dodecahedral faces. This is the most common type. The optic plane in this type is parallel to the long diagonal of the rhombic face, and X is perpendicular to this face. The acute bisectrix is positive, and the axial angle is about 56°. The dispersion is strong with $\rho < v$.

2. Hexoctahedral or topazolite type. In this case the exterior form is a dodecahedron, modified by vicinal hexoctahedral faces, which is made up of forty-eight unsymmetrical triangular pyramids whose bases form the hexoctahedral faces. The optic plane makes an angle somewhat variable in different samples (2° to 17°) with the long diagonal of the dodecahedral face, while X is also somewhat inclined from the perpendicular to this face. The acute bisectrix is negative.

3. Icositetrahedral or trapezohedral type. In this type the exterior form is a trapezohedron (211) which is made up of twenty-four pyramids whose bases form the trapezohedral faces. The optic plane is perpendicular to the symmetrical diagonal of the trapezohedral face to which the positive acute bisectrix is perpendicular.

4. Octahedral type. This type is known only in octahedral garnets from the island of Elba, which are composed of eight pyramids having their summits at the center of the crystal and their bases parallel with the faces of the crystal. Each pyramid is uniaxial, and the negative optic axis is perpendicular to the face of the crystal.

Finally, more than one of those types are sometimes present in a single crystal. Sometimes the crystal is made of zones or layers which may be mechanically separated; one zone will show one type and the next another type. In some crystals also the different types interpenetrate. Further, crystals are very often made up of isotropic and anisotropic parts arranged in various ways.

ALTER. Garnets are known to alter in various ways. They may change to chlorite, epidote, limonite, amphibole, feldspar, enstatite, spinel, biotite, hypersthene, calcite, etc.

OCCUR. Garnet in crystals often somewhat rounded is common in mica schist, hornblende and chlorite schists and gneisses. It is found also in many plutonic rocks, more rarely in volcanic rocks. It is common in crystalline limestones, especially in contact regions. It is sometimes found in massive form as a very abundant constituent in certain rocks, such as garnet felsite and eclogite.

DIAG. The crystal form of garnet is quite characteristic. In thin section garnets show no cleavage and very high relief, often accompanied by a shagreen surface (due to high refringence and hardness); they are usually isotropic and often pink in color. Andradite, uvarovite and grossularite are the only garnets that sometimes show distinct birefringence; these are the calciferous garnets. Brögger states that garnets formed directly from an igneous magma as well as those produced by the slow processes of regional metamorphism are isotropic, while those produced by hot solutions or by contact metamorphism often show an apparent anisotropic character. Some of the varying characters of the garnets may be tabulated as follows:—

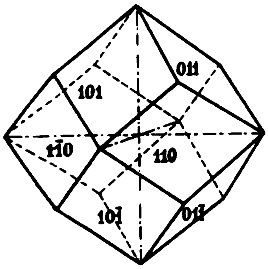

Fig. 126.
A simple crystal form of garnet.

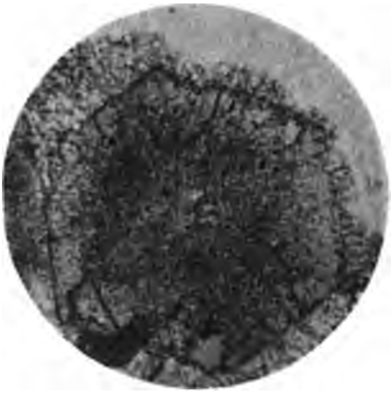

Fig. 127. Section of garnet showing crystal outline and high relief, in paragonite schist from Airolo, Italian Alps. H. 1046. One nicol. × 15.

| Name | Optic character | G. | Pyrognostic characters | Colors |
|---|---|---|---|---|
| **Andradite** | **Isotropic or anisotropic** | 3.8 to 4.1 | **Fusible to black magnetic globule** | **Yellow, brown red, black.** |
| **Uvarovite** | **Isotropic or anisotropic** | 3.4 | **Infusible. With borax reacts for chromium** | **Emerald green** |
| **Grossularite** | **Isotropic or anisotropic** | 3.4 to 3.6 | **Easily fusible to pale non-magnetic globule** | **White, yellow brown, red, green** |
| **Pyrope** | **Isotropic** | 3.7 to 3.8 | **Difficultly fusible to black non-magnetic globule** | **Red to nearly black** |
| **Almandite** | **Isotropic** | 4.1 to 4.3 | **Fusible to dark colored magnetic globule** | **Brown, red, black** |
| **Spessartite** | **Isotropic or indistinctly anisotropic** | 3.7 to 4.3 | **Readily fusible to black non-magnetic globule. Reacts for manganese** | **Various shades of red** |

Chemically garnets are orthosilicates of a trivalent and bivalent base with the general formula $R_3R'_2(SiO_4)_3$ in which R may be Ca, Mg, Fe, or Mn and R′ may be Al, Fe, or Cr. There are six theoretical types in the combination of these elements, but there are many occurrences showing gradations between these types. The classification follows:—

| Classified according to bivalent base. | Name | Chemical composition | Classified according to trivalent base |
|---|---|---|---|
| Calcium garnet | Andradite | $Ca_3Fe_2(SiO_4)_3$ | Iron garnet |
| | Uvarovite | $Ca_3Cr_2(SiO_4)_3$ | Chrome garnet |
| | Grossularite | $Ca_3Al_2(SiO_4)_3$ | Aluminum garnet |
| Magnesium garnet | Pyrope | $Mg_3Al_2(SiO_4)_3$ | |
| Iron garnet | Almandite | $Fe_3Al_2(SiO_4)_3$ | |
| Manganese garnet | Spessartite | $Mn_3Al_2(SiO_4)_3$ | |

## ANDRADITE. (Melanite).

ISOMETRIC $Ca_3Fe_2(SiO_4)_3$

PHYS. CHAR. Usually occurs in dodecahedrons or trapezohedrons. No cleavage. H. = 7. G. = 3.8-4.1.

OPT. PROP. Andradite usually shows birefringence, though it is often indistinct. The crystals may show the dodecahedral or hexoctahedral type of structure, or they may exhibit a combination of these types. In one case Lacroix reports andradite of the dodecahedral type with an optic angle of nearly 90° about the positive bisectrix. Often dark colored even in thin section, but color varying in mass from black to red, brown, greenish yellow, yellow.

$n = 1.8467$ Li $n = 1.8566$ Na $n = 1.8659$ Tl

ALTER. Andradite is known to alter to epidote, limonite, feldspar, and calcite.

OCCUR. Andradite is found in nepheline syenite, in some acid igneous rocks, in serpentine, in chlorite and other schists, and in crystalline limestones in regions of contact.

**Schorlomite** is a variety of andradite rich in titanium. Crystals trapezohedral or dodecahedral; usually massive. Cleavage unknown. G. = 3.81-3.88. Fusible at 3. Gelatinizes with HCl. Isotropic, or rarely indistinctly anisotropic. Color black, bluish, or brownish. Streak grayish black. In thin section translucent and dark brown to opaque. Rare.

DIAG. See page 243.

## UVAROVITE.

ISOMETRIC $Ca_3Cr_2(SiO_4)_3$

PHYS. CHAR. Crystals dodecahedral. No cleavage. H. = 7. G. = 3.4.

OPT. PROP. Uvarovite often shows birefringence; its structure is the dodecahedral. Even in thin section the color is green, usually rather dark. In mass it is emerald green.

$$n = 1.8318 \text{ Li} \quad n = 1.8384 \text{ Na} \quad n = 1.8449 \text{ Tl}$$

ALTER. Uvarovite alters in some cases to a dark green chlorite, doubtless containing chromium.

OCCUR. Rare. Found in gneiss, in serpentine, and in cavities in chromite; also in contact metamorphosed limestone.

DIAG. See, page 243.

## GROSSULARITE.

ISOMETRIC $Ca_3Al_2(SiO_4)_3$

PHYS. CHAR. The dodecahedral form is very common; the trapezohedron also occurs, and the hexoctahedron is found modifying these. Striations are common on the dodecahedral faces. H. = 6.5-7. G. = 3.4-3.6.

OPT. PROP. Grossularite is sometimes isotropic, but the variety *pyrenеite* is always anisotropic. It has the dodecahedral structure, and in each of the constituent pyramids the optic plane is parallel to the long diagonal of the rhombic face, while X is perpendicular to that face. The acute bisectrix is positive. The dispersion is strong with $\rho < v$.

$$(+) \quad 2V = 56\tfrac{1}{2}^\circ$$

$$n = 1.7368 \text{ Li} \quad n = 1.7468 \text{ Na} \quad n = 1.7593 \text{ Tl}$$

$$n_g - n_p = 0.0027 \quad n_g - n_m = 0.0021 \quad n_m - n_p = 0.0006$$

Color, white, gray, greenish, yellowish, brown, red. Colorless to yellowish brown in thin section.

ALTER. Grossularite is known to alter to epidote, chlorite, feldspar and calcite.

OCCUR. Grossularite is especially common in crystalline limestone; also found in schists, in veins, and in nepheline syenite.

DIAG. See page 243.

### PYROPE.

ISOMETRIC $Mg_3Al_2(SiO_4)_3$

PHYS. CHAR. Crystal form not common. Dodecahedral form is found; cubic faces, so rare in garnets, are also known. H. = 7.-7.5. G. = 3.65-3.8.

OPT. PROP. Always isotropic. Color red of various shades, rarely black. In thin section, red to yellowish brown.

$n = 1.7776$ Li $n = 1.8141$ Na $n = 1.8288$ Tl

ALTER. Pyrope alters to a green substance called kelyphite. This often forms a crust about the garnet grains. Microscopically it can be seen that this is not a distinct mineral, but usually an intergrowth of fibrous amphibole and feldspar. Pyrope also alters to chlorite.

OCCUR. Pyrope is found especially in peridotites and in the serpentines derived from them. It is found in the "blue ground" of the diamond mines of South Africa.

DIAG. See page 243.

### ALMANDITE.

ISOMETRIC $Fe_3Al_2(SiO_4)_3$

PHYS. CHAR. The common forms are the dodecahedron and trapezohedron. The faces are sometimes striated. Dodecahedral cleavage or parting indistinct. H. = 7.-7.5. G. = 4.1-4.3.

OPT. PROP. Always isotropic. Color red, brownish, violet red, black. In thin section brown to reddish.

$n = 1.8052$ Li $n = 1.8109$ Na $n = 1.8159$ Tl

ALTER. Almandite alters readily to chlorite and epidote. Further, when subject to the heat of enclosing volcanic rocks it is fused and on recrystallization forms a green spinel and hypersthene. Finally, alteration of almandite is also known to biotite, hornblende, scapolite, feldspar, hematite and limonite.

OCCUR. Almandite is common in granulites, pegmatites, gneisses, and schists. It is also found in amphibolites, and is an essential element of eclogite. It is rare in granite and in regions of contact metamorphism. In the mica schists it is associated especially with staurolite, cyanite and andalusite; in granulites it is often associated with tourmaline, sometimes with cordierite.

DIAG. See page 243.

## SPESSARTITE.

ISOMETRIC $Mn_3Al_2(SiO_4)_3$

PHYS. CHAR. The trapezohedron and dodecahedron are the common forms. H. = 7. G. = 3.77-4.27.

OPT. PROP. Usually isotropic; sometimes indistinctly anisotropic; it is then said to show the trapezohedral type of grouping.

$$n = 1.7940 \text{ Li} \quad n = 1.7991 \text{ Na}$$

Color red of various shades, or yellowish brown; in thin section pale pink.

ALTER. Spessartite is known to alter to biotite.

OCCUR. It is found in pegmatites, in micaschist, in quartzite, and in lithophyses in rhyolite. Uncommon.

DIAG. See page 243.

## GAYLUSSITE.

MONOCLINIC $a:b:c::1.490:1:1.444$ $CaCO_3 \cdot Na_2CO_3 + 5H_2O$

$$\beta = 78° 27'$$

PHYS. CHAR. Crystals often elongated || $a$; also wedge-shaped. Cleavage perfect || 110, difficult || 001. H. = 2.-3. G. = 1.94. Fuses easily to white enamel. Soluble in cold acid with effervescence; partly soluble in $H_2O$.

OPT. PROP. The plane of the optic axes and the acute bisectrix are normal to 010. The obtuse bisectrix Z makes an angle of 14° 48′ with the vertical axis in the acute angle $\beta$ in red light, and 13° 8′ in blue light. Optic angle considerable. Crossed dispersion strong with $\rho < v$.

$$(-) \quad 2E = 51° 38' \text{ Li}$$

$$n_g = 1.5233 \quad n_m = 1.5156 \quad n_p = 1.4435$$

$$n_g - n_p = 0.0798$$

Color white, yellowish. Luster vitreous. Colorless in section.

OCCUR. Deposited from waters of certain saline lakes. Rare.

**Pirssonite** ($CaCO_3 \cdot Na_2CO_3 + 2H_2O$) is related chemically, but is orthorhombic with $a:b:c::0.566:1:0.302$. Crystals prismatic, hemimorphic. Cleavage none. H. = 3.-3.5. G. = 2.35. Optic plane parallel to 001; acute bisectrix Z normal to 010. Birefringence very strong. $(+)$ $2E = 48° 14'$ $(2V = 32° 48')$: $n_g = 1.5751$, $n_m = 1.5095$, $n_p = 1.5043$; $n_g - n_p = 0.0708$. Colorless to white. Found with gaylussite. Rare.

**GEDRITE,** see amphibole group. **GEHLENITE,** see melilite group. **GEIKIELITE,** see ilmenite group. **GENTHITE,** see serpentine group.

## GERHARDTITE.

ORTHORHOMBIC $a:b:c::0.922:1:1.156$ $Cu(NO_3)_2 \cdot 3Cu(OH)_2$

PHYS. CHAR. Crystals short pyramids terminated by 001; pyramidal zone strongly striated. Cleavage highly perfect || 001, giving flexible laminæ; imperfect || 100. H. = 2. G. = 3.43. Fusible at 2 giving green flame. Soluble in dilute acids.

OPT. PROP. The plane of the optic axes is parallel to 010; the negative acute bisectrix is normal to 001. Optic angle large. Dispersion $\rho < v$. $2K = 76° 20'$ Na. Color deep emerald green. Streak light green. Pleochroic with Z blue, Y and X green.

OCCUR. Found with malachite in cuprite in Arizona. Very rare.

## GISMONDITE, see zeolite group.

## GLAUBERITE.

MONOCLINIC $a:b:c::1.220:1:1.027$ $Na_2SO_4 \cdot CaSO_4$
$\beta = 67° 49'$

PHYS. CHAR. Crystals tabular || 001, or prismatic with 110 or 111 prominent. Cleavage perfect || 001. H. = 2.5-3. G. = 2.7-2.85. Decrepitates and fuses easily to white enamel. Soluble in HCl. Partly soluble in $H_2O$. Taste slightly saline.

OPT. PROP. The plane of the optic axes is normal to 010 at ordinary temperatures; the negative acute bisectrix makes an angle of 31° with $c$ in the acute angle $\beta$. The sign and the position of X, Y, and Z remain sensibly constant, but the optic axes change position quite rapidly with change of temperature. At 5°C. the optic plane is normal to 010 for all colors, while at 85°C. the optic plane is parallel to 010 for all colors. At the same time the dispersion changes from horizontal with $\rho > v$ to inclined $\rho < v$. The dispersion is very strong, giving abnormal interference figures in white light.

$(-)\ 2E = 0°\text{-}17°$

| | | At 5°C. | 22°C. | 36°C. | 46°C. | 58°C. | 85°C. |
|---|---|---|---|---|---|---|---|
| Red light | $2E =$ | 16° 6′ | 13° 30′ | 11° 1′ | 8° 40′ | 0° | 10° 47′ |
| Yellow | $2E =$ | 14° 8′ | 11° 8′ | 8° 9′ | 0° | 7° 14′ | 13° 14′ |
| Green | $2E =$ | 11° 42′ | 8° 14′ | 0° | 7° 8′ | 10° 32′ | 15° 15′ |
| Blue | $2E =$ | 8° 51′ | 0° (at 18°) | 8° 42′ | 11° 8′ | 13° 2′ | 17° 7′ |

Color pale yellow or gray; sometimes brick red. Colorless in section.

ALTER. Alteration to calcite has been observed.

OCCUR. Usually in lake deposits associated with halite, polyhalite, anhydrite, thenardite, etc.

## GLAUCOCHROITE, see olivine group.

## GLAUCONITE.

MONOCLINIC? Axial ratio unknown $KFe(SiO_3)_2 + nH_2O$?

COMP. The exact composition is uncertain; the material analyzed is usually impure and results of analyses vary widely.

Phys. Char. Usually in granules, rarely as large as 0.1 mm. Granules long supposed to be amorphous; when much magnified crystalline character is evident; the grains are composed of interwoven laminæ. Cleavage distinct || 001. Cleavage lines often wavy. H. = 2. G. = 2.2-2.8. Easily fusible to a black glass.

Opt. Prop. The negative acute bisectrix is nearly normal to the cleavage 001. The optic angle is sometimes practically 0°, but usually larger.

$$(-)\quad 2E = 30^\circ - 40^\circ$$
$$n = 1.61$$
$$n_g - n_p = 0.020 \text{ about}$$

Color olive green, blackish green; by alteration becomes yellow to brownish. In thin section greenish, sometimes pleochroic, green to pale yellow, with maximum absorption when the cleavage laminæ are parallel with the lower nicol.

Occur. Glauconite is found only in marine sedimentary rocks. It is always associated with clastic elements, especially feldspar, quartz, muscovite, etc. It is being formed at present on the ocean bottoms at depths of about 600 to 5000 feet. It is usually intimately associated with animal remains, but less commonly it forms away from such organisms. It is often in grains of submicroscopic size, serving as a pigment of other minerals.

**Celadonite** is a mineral of similar composition of earthy aspect. Microscopically it is lamellar or fibrous. Cleavage perfect, as in micas. Very soft with greasy feel. G. = 2.6. Optically like glauconite; the optic angle is small, the sign is negative. Refringence moderate, $n = 1.63$. Color olive to apple green. In thin section pleochroic, with Z and Y dark green, X lighter green with yellowish tint. It is always a product of alteration; found in cavities in volcanic and metamorphic rocks.

Diag. The cryptocrystalline texture of the rounded grains is quite characteristic; celadonite is lamellar or fibrous.

**GLAUCOPHANE,** see amphibole group. **GMELINITE,** see zeolite group. **GOETHITE,** see diaspore group.

## GOLD.

Isometric Au

Comp. Usually alloyed with more or less Ag; sometimes also small amounts of Cu, Fe.

Phys. Char. Crystals octahedrons, dodecahedrons, or modified. Often elongated filiform, arborescent, reticulated. Granular, lammellar, massive. Twinning on 111. Cleavage none. Highly malleable. H. = 2.5-3. G. = 15.6-19.3. Easily fusible. Soluble in aqua regia.

Opt. Prop. Color and streak gold yellow grading to silver white with increase of silver. The presence of copper gives an orange tint to the color. Luster metallic. Opaque in thin section, but may be beaten into films which transmit a greenish light.

Occur. Found especially in quartz veins in igneous and metamorphic rocks; also found in calcite veins, and in various other types. Very sparingly found in rocks away from veins, as in serpentine. Abundant in some water-sorted gravels and conglomerates, both recent and ancient. Associated especially with pyrite, also, less commonly, with chalcopyrite, galena, sphalerite, etc.

**Silver** (Ag) is also isometric. Crystals like gold. No cleavage. H. = 2.5-3. G. = 10.5. Easily fusible. Soluble in $HNO_3$. Color and streak silver white. Luster metallic. Opaque. Found in veins in igneous and metamorphic rocks. Very rarely found disseminated in igneous rocks. Often associated with native copper, galena, chalcocite, cerargyrite, etc. Refringence very high ($n = 3.37$?).

**Copper** (Cu) is also isometric. Crystals octahedral, dodecahedral, cubic, very often modified by tetrahexahedrons. Often arborescent, filiform, etc. Massive. Twinning on 111 common. Complex grouping of crystals. No cleavage. H. = 2.5-3. G. = 8.84. Easily fusible. Soluble in $HNO_3$. Color copper red. Streak metallic shining. Luster metallic. Opaque. Alters to cuprite, malachite, rarely azurite. Found in veins in all kinds of rocks, also in amygdaloidal cavities, often associated with calcite, zeolites, etc., and somewhat disseminated in wall rocks, and in sedimentary rocks, especially sandstone. Refringence very high ($n = 2.93$?).

DIAG. The color alone is commonly distinctive for these metals. Further, gold is soluble only in aqua regia, and is soft and malleable; silver has no cleavage and tarnishes easily; copper has darker color, no cleavage, and is quite malleable.

**GOSLARITE**, see epsomite group.

## GRANDIDIERITE.

ORTH. Axial ratio unknown $(Na,H)_4(Mg,Fe)_7(Al,Fe)_{22}Si_7O_{50}$

PHYS. CHAR. Crystal faces unknown. Has two unequal cleavages || 100 and 010. G. = 2.99. Infusible and insoluble.

OPT. PROP. The plane of the optic axes is parallel to 001; the negative acute bisectrix is perpendicular to 100. The dispersion $\rho < v$ is very strong.

$$(-)\ 2V = 30^\circ$$
$$n_g = 1.6385 \quad n_m = 1.6360 \quad n_p = 1.6018$$
$$n_g - n_p = 0.0367$$

Color greenish blue. Luster vitreous. The pleochroism is extremely intense with X > Z > Y.

Z = pale bluish green
Y = colorless
X = greenish blue

ALTER. Alters readily to a green fibrous mineral similar to the alteration product (*kryptotile*) of prismatine.

OCCUR. Found in pegmatite and aplite of Madagascar with quartz, orthoclase and almandite.

Diag. Distinguished by its pleochroism resulting in deep color transverse to elongation and no color parallel to the elongation.

### GRAPHITE.

Hexagonal $c = 1.3859$ C

Phys. Char. Crystals are rare; they are usually rounded hexagonal lamellæ. Usually found in concentric foliated masses. Sometimes earthy and only cryptocrystalline. Perfect basal cleavage 0001; cleavage laminæ are flexible and not elastic. H. = 1.-2. Greasy feel. G. = 2.1-2.2. Infusible; deflagrates with $KNO_3$. Insoluble.

Opt. Prop. Color and streak black. Luster metallic. Opaque even in very thin sections.

Occur. Graphite is found in small amount in many igneous rocks; also sometimes in greater quantity in gneisses and schists. It is also found in contact rocks, in ordinary sedimentary rocks, in beds of coal that have been subject to metamorphism, and in meteorites.

Diag. Graphite deflagrates in a platinum spoon with nitre. producing potassium carbonate. Molybdenite resembles graphite in exterior characters, but it is fusible, giving sulphur coatings; it is attacked by nitric acid; it does not deflagrate, and it has a streak slightly greenish instead of black.

### GREENALITE.

Amorphous $FeSiO_3 + nH_2O$?

Comp. The exact composition is in doubt, since pure material is not available for analysis. Ferric iron is often present, sometimes in important amount. Mg commonly replaces a little Fe. Chemically, greenalite is closely related to glauconite, and to cronstedtite, chamosite, berthiérine, etc.

Phys. Char. Unknown except in amorphous state, and always in granules. G. = 2.8 +. Soluble in HCl.

Opt. Prop. Amorphous and isotropic. Color green, sometimes yellowish or brownish from alteration. In thin section green, brownish green, greenish yellow, brown, black; in reflected light green and yellow granules appear dark green or yellow; brown and black granules appear light green.

Occur. Abundant in the Lake Superior regions in cherts; on the Mesabi range the chief constituent of a rock called taconyte. Formed artificially by combining solutions of ferrous chloride and sodium silicate.

**Chamosite** is a chloritic mineral with $2E$ very small about X, and $n_g - n_p = 0.010$ to $0.012$. The pleochroism is weak with Z = Y pale green, X yellowish or colorless. Found in sedimentary rocks where it may constitute an iron ore.

**GREENOCKITE,** see cinnabar group. **GROSSULARITE,** see garnet group. **GRUENERITE,** see amphibole group.

## GYPSUM.

MONOCLINIC $a:b:c::0.6899:1:0.4124$ $CaSO_4 + 2H_2O$

$\beta = 80° 42'$

PHYS. CHAR. Crystals usually simple in habit, commonly flattened || 010; less commonly prismatic to acicular || *c*. Also foliated in masses or granular massive. Twinning common with twinning plane || 100 usually in contact twins of arrow-head shape. Twinning sometimes polysynthetic. Cleavage perfect || 010, imperfect || 100 and $\bar{1}11$. H. = 2. G. = 2.31-2.33. Fusible at 2.5-3, with reddish yellow flame color. Gives water in the closed tube. Soluble in HCl. Somewhat soluble in $H_2O$.

OPT. PROP. The plane of the optic axes is parallel to 010 at ordinary temperatures. The acute bisectrix Z makes an angle of 52° 30′ with *c* in the obtuse angle $\beta$. The angle of the optic axes varies with the temperature. The angle $2E$ is about 95° at 20°C.; at 115° C. it becomes 0°, and at a higher temperature the optic axes open out in a plane normal to 010. As this change occurs it is accompanied by a change in the dispersion, which is $\rho > v$ with strong inclined dispersion of the bisectrices at 15°C., but at 120°C. it is $\rho < v$ with horizontal dispersion of the bisectrices. Colorless.

$(+)\ 2V = 58°\ (2E = 95°)$

$n_g = 1.5296 \quad n_m = 1.5227 \quad n_p = 1.5204$

$n_g - n_p = 0.0092$

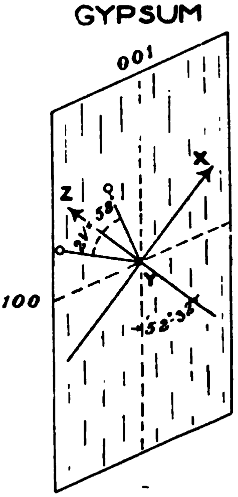

Fig. 128.
Optical orientation of gypsum.

OCCUR. Gypsum occurs in extensive masses in sedimentary rocks, especially limestones. It is often associated with halite as a product of evaporation of salt lakes, estuaries, etc. It is also found about volcanoes, the gases of the fumaroles reacting with the lime of lavas or other rocks to produce it. It is produced by the decomposition of sulphides, such as pyrite, in the presence of lime. It occurs occasionally in igneous rocks.

DIAG. Refringence low, birefringence rather weak, dispersion strong, one perfect cleavage, two imperfect cleavages, biaxial, positive.

**HAIDINGERITE,** see pharmacolite.

### HALITE.

ISOMETRIC NaCl

PHYS. CHAR. Crystals usually cubic. Massive cleavable to compact. Cleavage perfect || 100. Percussion figure on 100 with rays parallel to the binary axes of symmetry. H. = 2.5. G. = 2.14. Easily fusible, often with decrepitation. Soluble in $H_2O$; taste saline.

OPT. PROP. Usually isotropic; sometimes slightly anisotropic. Refringence low; $n = 1.5442$. Colorless, white, yellowish, reddish, bluish. The red color is due to the ferruginous inclusions, the blue color also seems to be due to inclusions of an iron compound. Luster vitreous.

INCL. Besides iron compounds, inclusions of gypsum, anhydrite, shale are common. Further, liquid inclusions often in "negative crystals" are not rare; they often contain gas bubbles, which may be movable. Such inclusions are sometimes megascopic in size.

OCCUR. Found chiefly in sedimentary deposits formed from evaporation in estuaries or in salt lakes. Occurs in rocks of various ages associated wih gypsum, anhydrite, polyhalite, carnallite, glauberite, etc. Formed rarely about volcanoes.

**Sylvite** (KCl) is similar in form and cleavage. H. = 2. G. = 1.98. Fuses with violet flame color. Soluble in $H_2O$; taste saline. Optically like halite, but $n = 1.4903$. Colorless, white or tinted by inclusions. Luster vitreous. Found in salt lake deposits with halite and carnallite; also formed about volcanoes.

**Salmiac** ($NH_4Cl$) is also isometric; twinning on 111. Stalactitic, globular, efflorescent. Cleavage imperfect || 111. H. = 1.5-2. G. = 1.528. Sublimes without fusion. Soluble in $H_2O$. Isotropic. Refringence moderate, $n = 1.6422$. Color white, yellowish, grayish. Luster vitreous. Found about volcanoes, near ignited coal seams, and in guano.

**Cerargyrite** (AgCl) is another isometric haloid. It grades into varieties containing bromine [*embolite,* Ag(Cl,Br) and *bromyrite,* AgBr] and iodine [*iodembolite,* Ag(Cl,Br,I)]. Crystals cubic in habit. Twinning on 111. Usually massive, encrusting. Cleavage none. H. = 1.-2. G. = 5.4-6. Insoluble in $HNO_3$; soluble in $NH_4OH$. Isotropic. Refringence very high. $n = 2.0611$, increasing in bromyrite to $n = 2.2533$. Color (cerargyrite) pearl gray, grayish green, whitish to colorless, turning to violet brown when exposed to sunlight; (embolite) grayish green and asparagus green to yellowish green, or yellow, turning dark on exposure; (bromyrite) yellow to amber yellow, slightly greenish especially externally, little altered on exposure; (iodembolite) sulphur yellow, sometimes greenish. Luster resinous. Found chiefly in veins in the oxydized zone, with other silver ores and with ores of copper, lead, etc.

### HAMBERGITE.

ORTHORHOMBIC $a:b:c::0.799:1:0.727$ $Be_2(OH)BO_3$

PHYS. CHAR. Crystals prismatic, vertically striated. Cleavage perfect || 010, imperfect || 100. H. = 7.5. G. = 2.35. Infusible, but subject to decrepitation. Insoluble, except in HF.

Opt. Prop. The plane of the optic axes is parallel to 010; the positive acute bisectrix is normal to 001. Birefringence very strong. Optic angle large; dispersion weak $\rho > v$.

$$(+)\ 2V = 87°\ 7'\ \mathrm{Na}\ \ (2H_a = 95°\ 42'\ \mathrm{Na})$$

$$n_g = 1.6311 \quad n_m = 1.5908 \quad n_p = 1.5595$$

$$n_g - n_p = 0.0716$$

Color grayish white. Luster vitreous.

Occur. Found in a pegmatitic vein in Norway. Very rare.

## HANKSITE.

Hexagonal $c = 1.014$ $9Na_2SO_4 \cdot 2Na_2CO_3 \cdot KCl$

Phys. Char. Crystals short prisms with pyramid and base, sometimes tabular. Cleavage distinct || 0001. H. = 3.-3.5. G. = 2.56. Fuses easily. Effervesces with acids. Soluble in $H_2O$; taste saline.

Opt. Prop. Uniaxial and negative. Refringence low; birefringence moderate.

$$n_g = 1.4807 \quad n_p = 1.4614$$

$$n_g - n_p = 0.0193$$

Color white, slightly yellowish. Luster vitreous.

Occur. Found with halite, thenardite, glauberite, etc. in California. Rare.

## HARDYSTONITE.

Tetragonal $c = ?$ $Ca_2ZnSi_2O_7$

Phys. Char. Crystals unknown; in granular masses; cleavage good || 001, sometimes distinct || 100 and 110. H. = 3.-4. G. = 3.4. Fuses with difficulty. Gelatinizes with HCl.

Opt. Prop. Uniaxial and negative. Refringence high. Color white.

$$n_g = 1.6691 \quad n_p = 1.6568$$

$$n_g - n_p = 0.0123$$

Occur. Found at Franklin Furnace with willemite, rhodonite, and franklinite. Rare.

## HARMOTOME, see zeolite group.

## HARSTIGITE.

Orthorhombic $a:b:c::0.715:1:1.015$ $H_7(Ca,Mn)_{12}Al_3(SiO_4)_{10}$

Comp. The exact formula is uncertain; Mg present in small amount.

Phys. Char. Crystals prismatic, with 010 and 011 prominent. Cleavage unknown. H. = 5.5. G. = 3.05. After ignition easily soluble in HCl.

Opt. Prop. The optic plane is parallel to 010; the acute bisectrix Z is normal to 100. Refringence high; birefringence weak. Optic angle large; dispersion $\rho < v$, weak.

$$(+)\ 2E = 90° 27' \text{ Na}$$
$$n_g = 1.6831 \quad n_p = 1.6782$$
$$n_g - n_p = 0.0049$$

Colorless. Luster vitreous.

Occur. Found in veins with garnet and rhodonite. Very rare.

**HATCHETTOLITE,** see pyrochlore group. **HAUTEFEUILLITE,** see vivianite. **HAUYNITE,** see sodalite group. **HEDENBERGITE,** see pyroxene group.

### HEINTZITE.

Monoclinic $a:b:c::2.914:1:1.734$ $KMg_2B_9O_{16}+8H_2O$?

$\beta = 80° 12'$

Phys. Char. Crystals pyramidal; often hemimorphic. Cleavage perfect || 100 and 001. H. = 4.-5. G. = 2.13. Very easily fusible with intense green flame color. Soluble in acids.

Opt. Prop. The optic plane and obtuse bisectrix X are normal to 010. The extinction in 010 is 7° to 15° from one of the cleavages in the acute angle $\beta$. $2H = 104° 27'$ Na. Colorless to white.

Occur. Found in salt deposits with boracite. Very rare.

### HELLANDITE.

Monoclinic $a:b:c::2.0646:1:2.1507$ $Ca[(Al,Y,Er,Fe)OH]_3Si_2O_8$

$\beta = 109° 45'$

Phys. Char. Crystals sometimes tabular || 010; twinning on 001 common. H. = 5.5, when unaltered. G. = 3.35-3.70. Soluble in HCl. Fusible easily.

Opt. Prop. The optic plane is normal to 010; Z makes an angle of 43½° with $c$ in the acute angle $\beta$. Twinning bands parallel to 100 are very common. Birefringence weak, and disappears gradually upon alteration; at the same time the angle $Z \wedge c$ slowly decreases. Optic angle large; apparently positive.

$$(+)\ 2V = 80° \pm$$
$$n_g - n_p = 0.01 \pm$$

Colorless to pale reddish brown in thin section without pleochroism.

Occur. Found in pegmatite dikes, with tourmaline, titanite, phenacite, thorite, and allanite. Very rare.

### HELVITE.

Isometric $(Mn,Fe)(Mn_2S)Be_3(SiO_4)_3$

Phys. Char. Commonly in tetrahedral crystals; rarely dodecahedral. Also in spherical masses. Cleavage || 111 in traces. H. = 6.-6.5. G. = 3.16-3.36. Fuses at 3. with intumescence to yellowish brown opaque bead. Soluble in HCl with separation of gelatinous silica and evolution of hydrogen sulphide.

Opt. Prop. The mineral is monorefringent.

$$n = 1.739$$

Color honey yellow, brownish, greenish, reddish; in thin section yellowish, often in triangular sections with irregular fracture and high relief.

Occur. Found in nepheline syenite, in pegmatite veins, in syenite, and in certain gneisses.

**Danalite** varies from helvite in containing some zinc. Color flesh-red to gray. Paler in color in section. Isotropic. Rare. Found in granite.

Diag. Monorefringence, high relief and triangular sections are quite characteristic. Chemically may be tested for manganese and sulphur.

## HEMAFIBRITE.

ORTHORHOMBIC $a:b:c::0.526:1:1.151$ $Mn_3(OH)_8AsO_4 + H_2O$

Phys. Char. Crystals prismatic, often fibrous radiated. Cleavage distinct || 010, less distinct || 110. H. = 3. G. = 3.6. Easily fusible. Soluble in HCl.

Opt. Prop. The optic plane is parallel to 100; the positive acute bisectrix is normal to 001. Optic angle large; dispersion $\rho > v$.

$$(+)\ 2E = 70° \pm$$

Color brownish red to black. Streak brick red. Luster vitreous to greasy.

Occur. Found in manganese mines in Sweden. Alters easily to a black foliated mineral. Very rare.

## HEMATITE.

RHOMBOHEDRAL $c = 1.35914$ $Fe_2O_3$

Phys. Char. Found in crystals of varied habit; rhombohedral faces usually prominent with or without the base. Also lamellar, columnar, fibrous, oolitic, granular, compact, or earthy. No cleavage, but sometimes parting || 0001, or $10\bar{1}1$, the latter due to polysynthetic twinning. H. = 5.5-6.5. G. = 4.9-5.3. Infusible but becomes magnetic in reducing flame. Soluble in HCl.

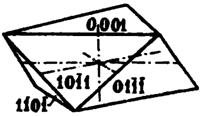

Fig. 129.
A symple crystal form of hematite.

Opt. Prop. Uniaxial and negative. The refringence[1] is very high and the birefringence very strong.

$$n_g = 3.042 \quad n_p = 2.797$$

$$n_g - n_p = 0.245$$

Color of crystals steel gray to iron black with good to brilliant luster. Earthy varieties red. Streak red. Opaque except in very thin scales which are blood red and slightly pleochroic, as follows:—Z brownish red, X yellowish red.

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[1] Försterling (*N. J. Beil. Bd.* XXV. 1908. p. 344) calculates the indices to be $n_p = 3.11$, $n_g = 2.88$.

ALTER. Hematite is a common alteration product, but it may itself alter to magnetite, siderite, limonite, pyrite, etc.

OCCUR. Hematite often occurs as microscopic inclusions and alteration products in many minerals and rocks, coloring them red. It is also found as a product of fumaroles in large crystals in eruptive rocks. It occurs as a product of contact metamorphism, and in various crystalline schists. It is common in many mineral, as well as in metalliferous, veins. Finally, it is very abundant in some ordinary sedimentary rocks. It is one of the most widely disseminated of minerals.

DIAG. Distinguished from magnetite and ilmenite by the deep red color of thin scales or of powder. Cinnabar has the color of massive hematite, but it has perfect hexagonal prismatic cleavage, is positive, and is of very restricted occurrence. Moreover, it has much higher specific gravity (8.-8.2) than hematite.

**HEMATOLITE**, see flinkite. **HERCYNITE**, see spinel group.

## HERDERITE.

MONOCLINIC $a:b:c::0.6307:1:0.4274$ $[Ca(F,OH)]BePO_4$

$\beta = 89° 54'$

PHYS. CHAR. Crystals often somewhat elongated || *a*, sometimes monoclinic in habit, but commonly pseudo-orthorhombic by penetration twinning on 001. Cleavage || 110 in traces. H. = 5. G. = 2.99-3.01. Fuses with difficulty, phosphorescing. Soluble in acids.

OPT. PROP. The plane of the optic axes is parallel to 010, and the negative acute bisectrix X makes an angle of about + 2° with *a*. Optic angle large; axial dispersion $\rho > v$; inclined dispersion distinct.

$$(-)\ 2V = 68°\text{-}74°\ \ (2E = 121°\text{-}128°)$$
$$n_g = 1.621\ \ n_m = 1.612\ \ n_p = 1.592$$
$$n_g - n_p = 0.029$$

Color yellowish to greenish white. Luster vitreous. Colorless in thin section.

OCCUR. Found in veins in granite; very rare.

DIAG. Distinguished from topaz by strong birefringence.

**HERRENGRUNDITE**, see brochantite. **HEULANDITE**, see zeolite group. **HIORTDAHLITE**, see pyroxene group. **HOMILITE**, see datolite group.

## HOPEITE.

ORTHORHOMBIC $a:b:c::0.578:1:0.476$ $Zn_3(PO_4)_2 + 4H_2O$

PHYS. CHAR. Crystals minute prismatic, or in aggregates of tabular (|| 100) to fibrous forms, the latter divergent. Also in reniform masses. Cleavage perfect || 100, less perfect || 010, and poor || 001. H. = 2.5-3. G. = 3.0-3.1. Fuses at about 5 to colorless globule. Soluble in acids.

OPT. PROP. The optic plane is parallel to 001; the acute bisectrix X is normal to 010. Birefringence strong. Optic angle large; dispersion $\rho < v$ weak. Sometimes apparently uniaxial by superposition of laminæ.

$$(-)\ 2E = 58^\circ\ 30'\ (2V = 36^\circ \pm).$$
$$n_m = 1.58\text{-}1.60$$

Color grayish white, reddish brown. Colorless in section.

**β-Hopeite** differs from α-hopeite (described above) in its weaker birefringence, and the variable position of the optic plane, either parallel or normal to 001. Also, the optic angle ($2E$) is only 32° in the former position, and 20° in the latter. Chemically the two varieties have the same formula, but the curves showing the loss of water upon heating are different.

**Parahopeite** is a name proposed for a triclinic phosphate of the same composition as hopeite. Crystals are lamellar to tabular || 100. Multiple twinning on 100 common. Cleavage perfect || 010. H. = 3.5-4. G. = 3.31. Soluble in HCl. Easily fusible. Optic plane and one optic axis nearly normal to 010, in which the extinction angle measured on *c* varies from 0° to 25°. Extinction angle on *c* in 100 is 30°. The obtuse bisectrix X is approximately normal to 100. Refringence, $n = 1.62$. Birefringence rather strong. Colorless. Found in cellular limonite in zinc deposits in Rhodesia.

OCCUR. Hopeite is found in cavities in calamine in zinc mines, and on bones in caves. Very rare.

**HORNBLENDE,** see amphibole group.

## HUEBNERITE.

MONOCLINIC $a:b:c::0.830:1:0.868$ $MnWO_4$

$$\beta = 89^\circ\ 22'$$

COMP. Often contains more or less Fe, thus grading to *wolframite,* $(Fe,Mn)WO_4$.

PHYS. CHAR. Crystals long prismatic; also tabular || 100. In bladed crystals or lamellar; columnar, granular, massive. Cleavage perfect || 010; parting || 100 and 102. H. = 5.-5.5. G. = 7.2-7.5. Fuses and reacts for Mn. Decomposed by aqua regia.

OPT. PROP. The plane of the optic axes and the obtuse bisectrix are normal to 010; the acute bisectrix Z makes an angle of + 17° with *c*. *Wolframite,* according to Miers, is uniaxial (?) and positive, with $n_g - n_p = 0.020$. Hübnerite has a large optic angle.

$$2V = 75^\circ \text{ Li}$$

Color brownish red to black, brown, grayish black. Streak yellowish brown, greenish gray, black. Pleochroic in thin section, with Z green, Y yellowish brown.

OCCUR. Found in veins with copper, manganese, tin ores; often associated with scheelite, fluorite, rhodochrosite, etc.

**Humite Group.**

The humite group consists of four minerals which are orthosilicates of magnesium containing the univalent radical [Mg(F,OH)]. From their symmetry prolectite, chondrodite and clinohumite are monoclinic, and humite is orthorhombic, but the variation of the angle $\beta$ is so slight in the former that it has not been measured. Mallard considers humite also monoclinic and attributes its apparent orthorhombic symmetry to submicroscopic twinning. The group is closely related to the olivine group.

In physical characters the minerals of the group are very similar. The monoclinic minerals show polysynthetic twinning with 001 as the twinning plane. This is supposed to exist as a submicroscopic twinning in the orthorhombic humite. They all have distinct cleavage parallel to 001; this is usually not well marked in thin section. H. = 6.-6.5. G. = 3.1-3.2. Color yellow to reddish brown in mass; colorless to bright yellow in thin section.

The length of the vertical axis varies with the number of atoms of magnesium that are present, as shown in the following table:—

| | $a : b : c$ | |
|---|---|---|
| Prolectite | $1.0803 : 1 : 3 \times 0.6287$ | $[Mg(F,OH)]_2MgSiO_4$ |
| Chondrodite | $1.0863 : 1 : 5 \times 0.6289$ | $[Mg(F,OH)]_2Mg_3(SiO_4)_2$ |
| Humite | $1.0802 : 1 : 7 \times 0.6291$ | $[Mg(F,OH)]_2Mg_5(SiO_4)_3$ |
| Clinohumite | $1.0803 : 1 : 9 \times 0.6288$ | $[Mg(F,OH)]_2Mg_7(SiO_4)_4$ |

## PROLECTITE.

MONOCLINIC $a : b : c :: 1.0803 : 1 : 1.8862$ $[Mg(F,OH)]_2MgSiO_4$

$\beta = 90°$

PHYS. CHAR. Similar to chrondodite. Only two fragmentary crystals known.

OPT. PROP. The plane of the optic axes is inclined 44° to 47° 15′ to 001, or 46° to 42° 45′ to *c*, and the positive acute bisectrix is normal to 010. The optic axial angle is large, and the relief is high.

$$(+)\ 2K_a = 79°\ 45'\ \text{Na}$$
$$n = 1.6703\ \text{Na}$$

Similar in other optical characters to chondrodite.

OCCUR. Known only at one locality in a vein in Sweden.

DIAG. Differs from other humites in extinction angle (45° ±) as measured on the cleavage || 001 or the polysynthetic twinning || 001.

## CHONDRODITE.

MONO. $a : b : c. : 1.0863 : 1 : 3.1445$ $[Mg(F,OH)]_2Mg_3(SiO_4)_2$

$\beta = 90°$

PHYS. CHAR. Crystals varied in habit, often flattened

|| 010. Twinning polysynthetic with 001 as twinning plane. Also massive, compact, and in embedded grains. Cleavage || 001 sometimes distinct. H. = 6.-6.5. G. = 3.1-3.2. Infusible. Gelatinize with acids. Give tests for fluorine.

Opt. Prop. The plane of the optic axes is normal to 010 and makes an angle of 26° to 30° with 001, and the positive acute bisectrix is normal to 010. The optic axial angle is large. Crossed dispersion with $\rho > v$.

$(+)\ 2H_a = 86°\text{-}89°\quad 2V = 79°\,40'\text{Na}$

$n_g = 1.639\quad n_m = 1.619\quad n_p = 1.607$

$n_g - n_p = 0.032$

Color light yellow to brownish red; in thin section chondrodite is colorless to brownish yellow. Pleochroism is distinct in colored varieties as follows:—

Z = pale yellow

(or colorless, or pale yellowish green).

Y = very pale yellow

(or colorless, or pale yellowish green).

X = pale golden yellow

(or brownish yellow).

The absorption is X>Z>Y.

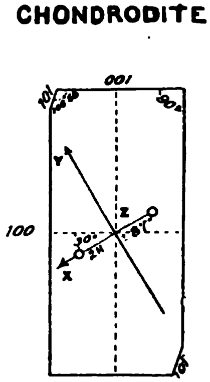

Fig. 130.
Optical orientation of chondrodite

Alter. All of the minerals of the humite group alter readily in the same way as olivine. Serpentine minerals are the common product, usually chrysotile or antigorite. Brucite is another common product. Finally, carbonates of magnesium may form.

Occur. Found in crystalline limestones, in limestone masses caught in volcanic rocks, and in some metalliferous veins. Clinohumite is more abundant than chondrodite, and humite less so.

Diag. Distinguished from the other humites by the extinction angle as measured on the cleavage or the polysynthetic twinning. See humite and clinohumite.

## HUMITE.

Orth. $a:b:c::1.0802:1:4.4034$ $[Mg(F,OH)]_2Mg_5(SiO_4)_3$

Phys. Char. Crystals usually small with many faces somewhat elongated || *a* or || *c*. Basal cleavage present, but not distinct in thin section. H. = 6.-6.5. G. = 3.1-3.2. Gelatinizes with acids. Gives test for fluorine. Infusible.

Opt. Prop. The plane of the optic axes is parallel to 001; the acute bisectrix Z is normal to 010. The optic axial angle is large. Dispersion $\rho > v$.

$(+)\ 2H_a = 78° \text{ to } 79° \text{ Li}\quad 2V = 67° 54'$
$n_m = 1.643$
$n_g - n_p = 0.032 \text{ to } 0.038$

Color white, yellow, brown; in thin section pleochroism is perceptible in colored varieties. The absorption is X>Z>Y.

Z = Y = very pale yellow to colorless.
X = pale golden yellow.

Alter. Similar to chondrodite.

Occur. Found in crystalline limestone, in limestone masses caught in volcanic rocks, and in some metalliferous veins.

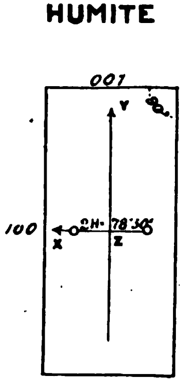

Fig. 131. Optical orientation of humite.

Diag. The extinction angle, measured on the cleavage (or on the polysynthetic twinning in the monoclinic species), in a section parallel to 010, i. e., normal to Z, the acute bisectrix, is 0° in humite, 7°-12° in clinohumite, 26°-30° in chondrodite, and about 45° in prolectite. Polysynthetic twinning is not present in humite. The humite group presents the same pleochroic colors as staurolite, but the golden yellow color occurs parallel to Z in the latter. It is very difficult to distinguish orthorhombic humite from the magnesian olivines without a chemical test for fluorine; however, the optic plane is parallel to the cleavage in humite and perpendicular to the best cleavage in olivine.

## CLINOHUMITE.

Mono. $a:b:c::1.0803:1:5.6588$ $[Mg(F,OH)]_2M_7(SiO_4)_4$
$\beta = 90°$

Phys. Char. Crystals usually with many faces. Twinning polysynthetic with 001 as twinning plane. Also massive. Cleavage || 001 sometimes distinct. H. = 6.-6.5. G. = 3.1-3.2. Infusible. Gelatinizes with acids. Gives test for fluorine.

Opt. Prop. The plane of the optic axes is normal to 010, and makes an angle 7°-12° with 001, and the positive acute bisectrix is normal to 010. The optic axial angle is large. Crossed dispersion with $\rho > v$ very weak.

$$(+)\ 2V = 76°\ 27' \quad 2H_a = 85°$$

$$n_g = 1.690 \quad n_m = 1.670 \quad n_p = 1.658$$

$$n_g - n_p = 0.032$$

Color brown, yellow, white; in thin section pleochroism is distinct in colored varieties, as follows:—

Z = pale yellow
(or colorless, or pale yellowish green).
Y = very pale yellow
(or colorless, or pale yellowish green).
X = pale golden yellow
(or brownish yellow).

**CLINOHUMITE**

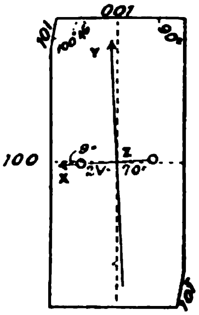

Fig. 132.
Optical orientation of clinohumite.

The absorption is X > Z > Y.

Alter. Similar to chondrodite.

Occur. Found in crystalline limestones, in limestone masses caught in volcanic rocks, and in some metalliferous veins. The various species of the group sometimes occur together.

Diag. Distinguished from olivine, staurolite and other humites as described under humite. Distinguished from titanolivine as follows:—In sections perpendicular to the positive bisectrix of twinned crystals the plane of the optic axes makes an angle of 7° to 12° (or 30° in chondrodite) with the twinning plane, while in titanolivine it is Y which makes an angle of 20° with the twinning plane.

## HUREAULITE.

Monoclinic $a:b:c::1.919:1:0.525$ $H_2Mn_5(PO_4)_4 + 4H_2O$

$$\beta = 84°\ 1'$$

Phys. Char. Crystals short prismatic, tabular. In sheaf-like groups; also massive, scaly or fibrous. Cleavage distinct || 100. H. = 5. G. = 3.15-3.19. Fusible. Easily soluble.

Opt. Prop. The optic plane and the negative acute bisectrix are normal to 010; $Z \wedge c = +75°$. Optic angle large; axial dispersion $\rho < v$ strong with distinct crossed dispersion.

$$(-)\ 2E = 173°\ 52'$$

Color orange red, rose violet, pink, grayish, nearly colorless.

Occur. Found in pegmatitic veins in granite. Rare.

**HUSSAKITE,** see xenotime. **HUTCHINSONITE,** see smithite. **HYALOPHANE,** see feldspar group.

## HYDRARGILLITE. (Gibbsite).

Monoclinic $a:b:c::1.7089:1:1.9184$ $Al(OH)_3$
$\beta = 85° 29'$

Phys. Char. Crystals uncommon; hexagonal in appearance by the presence of 001, 100 and 110; usually flattened || 001. Often in microscopic lamellæ. Also in concretions, in stalactites, or in crusts. Cleavage micaceous || 001 giving lamellæ slightly flexible; percussion figures similar to those of the micas, producing lines perpendicular to the sides of the hexagon. Twinning common of various types. The twinning plane may be 001, or a plane normal to 001 making an angle of 119° 10′ with 100 in 001, and an angle of 0° 32′ with 110 in 001; in this type of twinning the basal planes are parallel, while the zone 001 : 100 of one crystal coincides with the zone 001 : 110 of the other. Other types of twinning occur more rarely—these types may combine in a single crystal like the albite and pericline twinning in the feldspars. H. = 2.5-3.5. G. = 2.3-2.42. Infusible; gives water in the closed tube. Soluble in sulphuric acid.

Opt. Prop. The variations observed in the optic properties are probably connected with the temperatures which the minerals experienced at the time of their formation (or later), since heat has very marked effect upon the optic angle and position of the optic elements. At ordinary temperatures the plane of the optic axes is usually perpendicular to 010, the plane of symmetry, and the positive acute bisectrix makes an angle with the vertical axis varying in different occurrences from 21° to 44°. The angle of the optic axes decreases with increasing temperature until at about 27°C. the mineral is sensibly uniaxial for blue; above that temperature the optic axes open out with increasing temperature in 010, the plane of symmetry. Upon cooling the change reverses itself. In nature the mineral occurs with the optic angle in any of the positions thus produced by heat. The refringence is low, and the birefringence moderate. The angle of the optic axes is always small, and may be 0°. Dispersion $\rho > v$ strong.

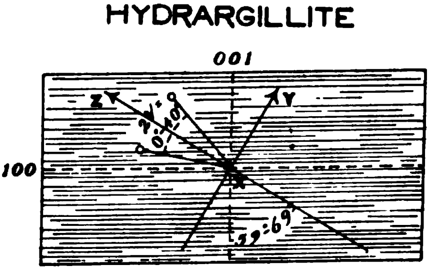

Fig. 133. Optical orientation of hydrargillite.

$$(+)\ 2V = 0°\text{-}40°$$
$$n_g = 1.5577 \quad n_m = n_p = 1.5347$$
$$n_g - n_p = 0.023$$

These measures were made upon the mineral from Norway, which is uniaxial. The indices must vary with the varying optic angle, and the birefringence probably varies also. On Brasilian hydrargillite $n_g - n_p = 0.019$ according to Lacroix.

Color white, grayish, etc.; colorless in thin section.

OCCUR. Often associated with corundum and emery; also a common decomposition product of feldspars in laterite, and in basalts altered to bauxite.

DIAG. Distinguished from kaolinite by the strong birefringence, from calcite and muscovite by the optic sign and the distinctly inclined extinction, from brucite and wavellite by the inclined extinction and chemical reactions.

### HYDROMAGNESITE.

ORTH. $a:b:c::1.038:1:0.465$ $3MgCO_3 \cdot Mg(OH)_2 + 3H_2O$

PHYS. CHAR. Crystals small, acicular or bladed; in tufts or crusts; massive. Cleavage unknown. H. = 3.5. G. = 2.14-2.18. Infusible. Soluble with effervescence.

OPT. PROP. The optic plane is parallel to 001; therefore Y is parallel to the prism and the elongation is ±. Refringence low; $n_g = 1.538$, $n_m = 1.530$, $n_p = ?$; $n_g - n_p = 0.015$ approx.

Color white to grayish or yellowish. In thin section colorless.

OCCUR. Found chiefly in serpentine as an alteration product; sometimes associated with, and an alteration product of, brucite.

### HYDRONEPHELITE, see zeolite group.

### HYDROTALCITE (Völknerite),

HEXAGONAL Axial ratio unknown $Al(OH)_3 \cdot 3Mg(OH)_2 \cdot 3H_2O$

PHYS. CHAR. Usually fibrous; sometimes foliated. Cleavage perfect || 0001. Feel greasy. H. = 2. G. ≐ 2.04-2.09. Gives much water in the closed tube. Infusible, but exfoliates somewhat. Soluble.

OPT. PROP. Uniaxial and negative. Refringence very low; birefringence rather weak.

$$n = 1.47$$
$$n_g - n_p = 0.014$$

Color white; luster pearly. Colorless in thin section.

OCCUR. Found in crystalline schists and serpentine. Rare.

**Pyroaurite** differs from hydrotalcite in containing $Fe_2O_3$ instead of alumina. It occurs in hexagonal or rounded plates with $c = 3.607$. Yellow to brownish. Negative and uniaxial, with weak birefringence.

**Diag.** Hydrotalcite is distinguished from brucite by its opposite sign, stronger birefringence, and much lower refringence; it also contains alumina.

### ICE.

| Hexagonal | $c = 1.403$ | $H_2O$ |
|---|---|---|

**Phys. Char.** Complete crystals rare; often in skeleton snow crystals of hexagonal symmetry. Usually tabular || 0001; also granular massive. Gliding plane || 0001 developed by pressure. H. = 1.5. G. = 0.918. Becomes water at 0° C.

**Opt. Prop.** Uniaxial and positive. Refringence lower than that of any other mineral; birefringence weak.

| | At 8°C. | At 8°C. | At 3.8°C. |
|---|---|---|---|
| $n_g =$ | 1.3037 Li | 1.3133 Na | 1.3163 Tl |
| $n_p =$ | 1.2970 Li | 1.3090 Na | 1.3107 Tl |
| $n_g - n_p =$ | 0.0067 Li | 0.0043 Na | 0.0056 Tl |

Colorless to white. In thick masses pale blue.

**Occur.** Abundant as a temporary constituent of surface rocks filling pores, fractures and cavities in winter in cold climates; also found occasionally at some depth below the surface. Also formed over lakes in crusts or layers composed of large acicular, irregularly arranged aggregates, or prisms arranged with vertical axes all normal to surface of water. In glaciers forming large masses whose texture is like that of granular limestone. In snow crystals of skeleton hexagonal forms of great variety. In frost often dendritic, stellate, etc. In hail anhedral crystalline aggregates.

### Ilmenite Group.

The ilmenite group includes several titanates of iron, magnesium or manganese. These minerals are chemically closely allied to perovskite ($CaTiO_3$), while crystallographically they are closely related to hematite ($FeFeO_3$) and corundum ($AlAlO_3$). We follow Lacroix (*Min. Fr.* III. 284) in assigning the name crichtonite to $FeTiO_3$ and ilmenite to $Fe(Ti,Fe)O_3$. These minerals are rhombohedral. They are as follows:—

| | | | |
|---|---|---|---|
| Crichtonite | $c = 1.3846$ | | $FeTiO_3$ |
| Ilmenite | $c = 1.3846$ | $m FeTiO_3 + n Fe_2O_3$ or | $Fe(Ti,Fe)O_3$ |
| Geikielite | $c = ?$ | | $MgTiO_3$ |
| Pyrophanite | $c = 1.369$ | | $MnTiO_3$ |

Crichtonite is relatively rare, ilmenite being much more abundant. It does not differ in character from the latter.

## ILMENITE (Menaccanite).

RHOMBOHEDRAL $c = 1.3846$ $Fe(Ti,Fe)O_3$

PHYS. CHAR. Crystals commonly show rhombohedral and basal faces with flattening || 0001. Also acute rhombohedrons with the base, prisms, etc. Often in thin laminæ; also massive. Twinning with 0001 as the twinning plane and rotation of 30°; also with $10\bar{1}1$ as twinning plane. Cleavage or parting || 0001. H. = 5.-6. G. = 4.5-5. Nearly infusible. Slowly soluble in HCl. The most rapid and convenient test for titanium chemically is to add a drop of this solution to a solution of morphine in concentrated $H_2SO_4$ producing a crimson color, or to a solution of thymol producing a garnet red, or to a solution of of phenol or gallic acid producing a brick red color.

OPT. PROP. Opaque; rarely translucent and dark brown in very thin sections. Luster metallic or submetallic; color iron black (crichtonite, violet black) sometimes brownish in reflected light. Sections of crystals hexagonal.

ALTER. Alters often to leucoxene, which is supposed to be a variety of titanite; this may be accompanied by the formation of rutile. Much more rarely alters to octahedrite; in the phyllites it sometimes alters to siderite and rutile.

OCCUR. A common, but sparsely distributed, constituent of igneous rocks; it is also common in small amount in many metamorphic rocks; finally it occurs in many veins, and also in alluvial sands.

DIAG. In thin section distinguishable from magnetite only when the alteration product (leucoxene) is present. Chemically it is characterized by the presence of titanium with iron. Non-magnetic.

## GEIKIELITE.

RHOMBOHEDRAL $MgTiO_3$

PHYS. CHAR. Massive, in pebbles. One perfect and one imperfect cleavage, nearly at right angles. H. = 6. G. = 3.98-4. Infusible. Slowly soluble in HCl. Reactions for titanium.

OPT. CHAR. Color bluish or brownish black. Translucent in thin section with purple color. Uniaxial and negative. Refringence very high; birefringence very strong. Luster metallic to adamantine.

OCCUR. Found in gem mines in Ceylon. Rare.

DIAG. Purple, uniaxial and negative with strong birefringence. Contains titanium.

## PYROPHANITE.

RHOMBOHEDRAL $c = 1.369$ $MnTiO_3$

**PHYS. CHAR.** In very thin tabular crystals or scales, basal plane prominent and brilliant, with rhombohedrons. Perfect rhombohedral cleavage || $02\bar{2}1$, also cleavage || $10\bar{1}2$. H. = 5. G. = 4.54. Soluble in HCl. Reacts for titanium.

**OPT. PROP.** Uniaxial and negative. High refringence and very strong birefringence.

$$n_g = 2.481 \text{ (Na)} \quad n_p = 2.210$$
$$n_g - n_p = 0.271$$

Color dark blood red; streak ocher yellow, slightly greenish. Luster brilliant, vitreous to submetallic. In thin section yellowish red, not pleochroic.

**OCCUR.** Found in the Harstig mine in Sweden. Rare.

**DIAG.** Yellowish red, negative, uniaxial with very strong birefringence. Contains titanium and manganese.

## ILVAITE.

ORTHORHOMBIC $a:b:c::0.6665:1:0.4427$ $CaFe_2(FeOH)(SiO_4)_2$

**PHYS. CHAR.** Commonly in vertically striated prisms elongated || *c*; pyramid faces also striated. Also compact. Cleavage distinct || 001 and 010, indistinct || 110 and 100. H. = 5.5-6. G. = 3.99-4.05. Fusible at 2.5 to black magnetic bead. Gelatinizes with HCl.

**OPT. PROP.** The plane of the optic axes is parallel to 100 and the positive acute bisectrix is normal to 001. Cleavage indistinct in thin section. Relief high. Optic axial angle large in some cases, less in others.

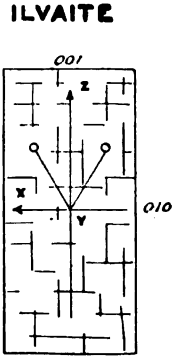

Fig. 134. Optical orientation of ilvaite.

$$(+)\ 2E = 60° \pm$$
$$n_m = 1.89$$

Color iron or grayish black; streak grayish black. Luster submetallic. Opaque except in thin section. Pleochroism intense in thin section; according to Böggild ilvaite has distinct pleochroism even in reflected light. Absorption Z > Y > X.

| Transmitted light. | Reflected light. |
|---|---|
| $Z = c =$ dark green to opaque | green |
| $Y = a =$ brown, nearly opaque | brown |
| $X = b =$ clear brown to brownish yellow | brown |

**ALTER.** Commonly alters to limonite.

**OCCUR.** Found in iron ore in Tuscany; as a contact mineral in crystalline limestone in Nassau; common as an alteration product of arfvedsonite and ægirine in alkaline syenites and granites of Greenland and some other districts. Rare.

**DIAG.** Crystal form quite characteristic. In thin section when translucent it has the brown color and intense pleochroism of ænigmatite from which it differs by its parallel extinction, maximum absorption parallel to the best cleavage, and easy attack by acids.

### IODYRITE.

HEXAGONAL $c = 0.820$ AgI

PHYS. CHAR. Crystals prismatic, hemimorphic. Twinning rare on $30\bar{3}4$. Also massive and lamellar. Cleavage perfect || 0001; lamellæ flexible. Soft. G. = 5.6-5.7. Fuses, giving fumes of I and Ag globules.

OPT. PROP. Uniaxial and positive. Refringence very high; birefringence strong. Suddenly becomes isometric and isotropic at 146°C.

$$n = 2.1816 \text{ Na}.$$

Color yellow to yellowish green; sometimes brownish. Streak yellow.

OCCUR. Found in veins in silver mines. Rare.

### IRON.

ISOMETRIC Fe

PHYS. CHAR. Usually massive; rarely in cubic or octahedral crystals with perfect cubic cleavage. Strongly magnetic. H. = 4.-5. G. = 7.3-7.8. Fusible at about 1500°C. Soluble to a yellow solution in HCl.

OPT. PROP. Opaque; color iron black to steel gray. Luster metallic. In thin section color and luster only observed by reflected light.

ALTER. Alters rapidly to limonite when exposed to the air.

OCCUR. Rare. Found in some igneous rocks very sparingly. Large masses found in Greenland in basalt. Iron is found in meteorites, in some cases making up the entire mass, in other cases a large portion, and in still other cases a small part of the whole. Meteoric iron always contains nickel (5% to 10% commonly) and a little cobalt. In this respect it differs from native iron. Further it shows Widmanstätten figures when etched by dilute nitric acid upon a smooth surface.

**JADEITE,** see pyroxene group. **JOHNSTRUPITE,** see mosandrite.

### KAINITE.

MONOCLINIC $a:b:c::1.219:1:0.586$ $MgSO_4 \cdot KCl + 3H_2O$

$$\beta = 85° \, 6'$$

PHYS. CHAR. Crystals tabular || 001, or pyramidal. Granular massive; encrusting. Cleavage distinct || 100, also || 110 and 010. H. = 2.5-3. G. = 2.06-2.2. Soluble easily in $H_2O$.

OPT. PROP. The optic plane is parallel to 010; the negative acute bisectrix makes an angle of 8° to 10° with $c$ in the acute angle $\beta$. Optic angle large; inclined dispersion very distinct with $\rho > v$ very weak.

$$(-) \quad 2V = 84° \, 33' \text{ Na} \quad (2E = 141° \pm)$$

$$n_g = 1.5203 \quad n_m = 1.5061 \quad n_p = 1.4948$$

$$n_g - n_p = 0.0255$$

Color white or colorless to dark flesh red. Colorless in section.

Occur. Found with picromerite, halite, sylvite, etc., in deposits of salt lakes or lagoons. Rare.

### KALINITE.

Isometric $K_2SO_4 \cdot Al_2(SO_4)_3 + 24H_2O$

Phys. Char. Usually fibrous, encrusting, or massive. Artificial crystals often octahedral; also cubic or modified. Twinning on 111. H. = 2.-2.5. G. = 1.75. Fuses in its water of crystallization and froths. Soluble in $H_2O$.

Opt. Prop. Normally isotropic, but molecular strain often produces birefringence. Refringence low, $n = 1.4557$. Color white. Luster vitreous.

Occur. Found as an efflorescence on argillaceous minerals. Uncommon.

**KALIOPHILITE,** see nephelite group.

### KAOLINITE.

Monoclinic $a:b:c::0.5748:1:1.5997$ $H_4Al_2Si_2O_9$

$\beta = 83° 11'$

Phys. Char. Crystals usually pseudohexagonal in thin hexagonal plates or scales, sometimes in fan-shaped groups. Other faces rare. Twinning similar to that of the micas and chlorites common; other twinning rare. Usually in clay-like masses, compact, with greasy feel when pure. Perfect basal cleavage. Laminæ flexible, inelastic. H. = 2.-2.5. G. = 2.6-2.63. Infusible. Yields water. Insoluble.

Opt. Prop. The plane of the optic axes and the obtuse bisectrix are normal to 010; the negative acute bisectrix makes an angle of 20° with a normal to 001 in the acute angle $\beta$. The angle of the optic axes is large; by superposition of lamellæ it may appear small; the birefringence is weak.

$$(-)\ 2V = 68°(90°?)$$

$$n = 1.563$$

$$n_g - n_p = 0.007$$

Colorless, white, rarely yellowish, brownish, etc. Luster on cleavage surface pearly; elsewhere sub-pearly to earthy. Colorless in thin section.

Occur. One of the common alteration products of feldspar; also of nepheline, scapolite and other silicates. Occurs in large masses in clay beds as a result of decomposi-

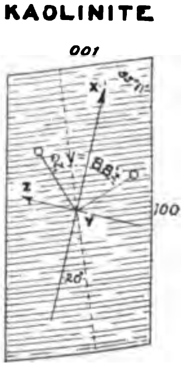

Fig. 135.
Optical orientation of kaolinite.

tion of feldspathic rocks. Clay usually contains some quartz and limonite as well as kaolinite. Large scaly kaolinite often found associated with iron ores in the Coal Measures. Also found as a vein filling in fissures in various rocks.

DIAG. Distinguished from muscovite, talc, and hydrargillite by its weak birefringence, large optic angle and infusibility; distinguished from pyrophyllite by its weak birefringence, its negative bisectrix not normal to 001, its infusibility, and its insolubility.

### KATOFORITE, see amphibole group.

### KIESERITE.

MONOCLINIC $a:b:c::0.915:1:1.757$ $MgSO_4 + H_2O$

$\beta = 89° 6'$

PHYS. CHAR. Crystals pyramidal, rare. Usually massive granular, compact. Cleavage perfect ‖ $\bar{1}11$ and $\bar{1}13$, imperfect ‖ 111, 101 and 012. H. = 3.-3.5. G. = 2.57. Easily fusible. Slowly soluble in $H_2O$.

OPT. PROP. The optic plane is parallel to 010; the positive acute bisectrix makes an angle of 76° with *c*. Optic angle large; inclined dispersion distinct with $\rho > v$.

$$(+) \quad 2E = 90° \text{ Na.}$$

$$n = 1.46$$

Color white, grayish to yellowish.

OCCUR. Found in salt beds at Stassfurt and elsewhere, often associated with carnallite and gypsum. Rare.

**Sulphoborite** $(2MgSO_4 \cdot 4MgHBO_3 + 7H_2O)$ is an orthorhombic magnesium salt with $a:b:c::0.620:1:0.810$. Crystals small prismatic. Cleavage distinct ‖ 110, indistinct ‖ 001. H. = 4. G. = 2.4. Fusible with intumescence. Soluble in acids. Optic plane parallel to 010; acute bisectrix X normal to 001. $(-)$ $2H_a = 79° 26'$ Na; $n_g = 1.5443$; $n_m = 1.5396$, $n_p = 1.5272$; $n_g - n_p = 0.017$. Colorless or stained. Found in salt mines with kieserite, anhydrite, carnallite, etc.

### KOPPITE, see pyrochlore group.

### KORNERUPINE (Prismatine).

ORTHORHOMBIC $a:b:c::0.854:1:?$ $MgAl_2SiO_6$

PHYS. CHAR. In fibrous to columnar aggregates with distinct prismatic cleavage. H. = 6.5. G. = 3.27-3.34. Infusible; insoluble.

OPT. PROP. The optic plane is parallel to 100; the negative acute bisectrix is normal to 001. Axial angle variable, $2E = 14°-32°$ (kornerupine), and in prismatine the dispersion is $\rho > v$ weak, with $2E = 65° 30'$ Na ($2V = 37° 34'$ Na).

$$n_g = 1.6818 \quad n_m = 1.6805 \quad n_p = 1.6691$$

$$n_g - n_p = 0.0127$$

Color white, gray, yellowish to brownish, rarely greenish. In thin section kornerupine is colorless and prismatine is yellowish; in thick sections prismatine has weak pleochroism with Z greenish to colorless, Y brownish yellow, X clear wine yellow.

Occur. Kornerupine is found with cordierite in a rock composed of mica, hornblende and sapphirine; prismatine occurs in granulite with albite, garnet, and tourmaline. Very rare.

Diag. Kornerupine differs from sillimanite in having negative elongation and weaker birefringence, from andalusite in higher refringence and smaller optic angle, and from topaz in having prismatic cleavage, higher refringence and negative elongation.

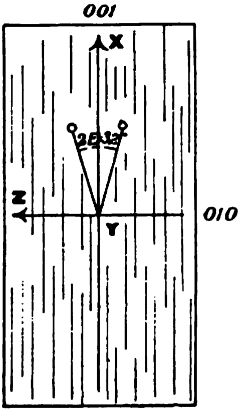

Fig. 186. Optical orientation of kornerupine.

## KROEHNKITE.

Monoclinic $a:b:c^1::0.5229:1:0.4357$ $Na_2Cu(SO_4)_2+2H_2O$

$\beta=56° 17'$

Phys. Char. Crystals irregular short prisms often twinned, and in fibrous aggregates, or crusts, Twinning common on 001. Cleavage perfect || 010, distinct || 011. H. = 2.5-3. G. = 2.06. Fuses easily after decrepitation. Soluble in water.

Opt. Prop. The optic plane is parallel to 010; the acute bisectrix X makes an angle of +48°-49° with $c$. $X_r \wedge c > X_{bl} \wedge c$. The refringence is moderate, and the birefringence very strong. The optic angle is large; the dispersion is inclined, with $\rho < v$, weak.

$$(-)\ 2V = 78°\ 40'\ \text{Na}.$$

$$n_g = 1.6013 \quad n_m = 1.5775 \quad n_p = 1.5437$$

$$n_g - n_p = 0.0576$$

Color deep to pale blue in mass.

Occur. Found with atacamite, brochantite and copiapite in Chile. Very rare.

**KTYPEITE,** see aragonite. **LABRADORITE,** see feldspar group. **LANARKITE,** see leadhillite.

## LANGBEINITE.

Isometric $K_2Mg_2(SO_4)_3$

Phys. Char. Crystals tetrahedral; highly modified. H. = 3.-4. G. = 2.81-2.86. Tasteless. Absorbs water rapidly from the air.

Opt. Prop. Isometric. Index $n = 1.5329$. Shows no circular polarization. Colorless, white. Luster greasy to vitreous.

Occur. Found in salt deposits taking the place of polyhalite. Rare.

**LANGITE,** see brochantite.

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[1] Palache and Warren: *Amer. Jour. Sc.* XXVI. 1908. p. 342.

## LANTHANITE.

ORTHORHOMBIC $a:b:c::0.953:1:0.902$ $La_2(CO_3)_3+9H_2O$

PHYS. CHAR. Crystals thin plates || 001; also granular, earthy. Cleavage micaceous || 001. H. = 2.5-3. G. = 2.61. Infusible. Effervesces in acids.

OPT. PROP. The optic plane is parallel to 100; the negative acute bisectrix is normal to 001. Optic angle large; dispersion small $\rho < v$. (—) $2E = 108° 1'$ Li.

Color grayish white, pink or yellowish. Luster pearly or dull.

OCCUR. Found with cerite or allanite; also with zinc ores in limestone. Rare.

## LAUMONTITE, see zeolite group.

## LAURIONITE.

ORTHORHOMBIC $a:b:c::0.738:1:0.835$ Pb(OH)Cl

PHYS. CHAR. Crystals minute, prismatic, flattened || 010. Cleavage distinct || 100. H. = 3.-3.5. Easily fusible. Soluble in $HNO_3$.

OPT. PROP. The optic plane is parallel to 010; the negative acute bisectrix is normal to 100. Refringence extremely high. Colorless.

$$(—)\ 2V = 81° 32'$$

$$n_g = 2.1580 \quad n_m = 2.1161 \quad n_p = 2.0767$$

$$n_g - n_p = 0.0813$$

OCCUR. Found with phosgenite and cerussite in cavities of very old lead slags acted upon by sea waters in Greece.

## LAVENITE.

MONOCLINIC $a:b:c::1.0964:1:0.715$ $Na(ZrO.F)(Mn,Ca,Fe)(SiO_3)_2$
$\beta = 69° 42'$

PHYS. CHAR. Crystals prismatic or tabular || 100; also in embedded grains. Twinning plane 100; sometimes as twinning lamellæ. Cleavage || 100 good, and visible in thin section. H. = 6. G. = 3.5. Fusible to a black scoria. Difficultly soluble in HCl.

OPT. PROP. The plane of the optic axes is parallel to 010; the negative acute bisectrix makes an angle of about 20° with the vertical axis in the acute angle $\beta$. Relief high like that of epidote. Birefringence stronger than that of olivine. Optic axial angle large. Dispersion very weak.

$$(—)\ 2V = 79° 46'$$

$$n_m = 1.750$$

$$n_g - n_p = 0.03$$

Color light yellow to brown. Pleochroism very strong, especially in dark colored varieties. Absorption Z > Y > X.

| yellow crystals | brown crystals |
|---|---|
| Z = golden yellow | brownish yellow to orange red |
| Y = colorless | greenish yellow |
| X = colorless | clear wine yellow |

ALTER. Alteration rare, but may change to

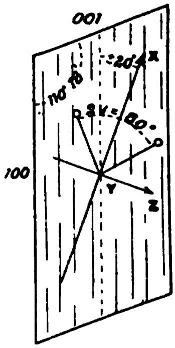

Fig. 137. Optical orientation of låvenite.

fluorite, zircon, hematite, or limonite, and certain unknown minerals.

Occur. Rare. Found in pegmatite dikes in nepheline syenite and related rocks in Norway, Brazil, France, U. S., etc.

Diag. Distinguished from epidote, which sometimes has the same color, by a different pleochroic formula and a large extinction angle (20°) in the zone of elongation; distinguished from wöhlerite and rinkite by its strong birefringence, and strong pleochroism.

## LAWSONITE.

Orthorhombic $a:b:c::0.665:1:0.738$ $H_4CaAl_2Si_2O_{10}$

Phys. Char. Crystals large, prismatic or tabular || 001. Twinning on 110. Cleavage perfect || 010 and 001, indistinct || 110. Prismatic cleavage often prominent in thin section. H. = 8. G. = 3.08-3.09. Easily fusible to colorless blebby glass. Insoluble, but gelatinizes after ignition.

Opt. Prop. The plane of the optic axes is parallel to 010; the positive acute bisectrix is normal to 001. Optic angle large. Refringence high; birefringence rather strong.

$$(+)\ 2V = 84^\circ 6'\ \text{Na}.$$

$$n_g = 1.6840 \quad n_m = 1.6690 \quad n_p = 1.6650$$

$$n_g - n_p = 0.019\text{-}0.021$$

Color pale blue to grayish blue: also colorless to greenish; colors often in bands parallel to the prism face. Colorless in thin section. Pleochroic in thick sections, with absorption X > Y > Z, and X blue, Y yellowish or colorless, Z colorless.

Occur. Lawsonite is produced by regional metamorphism in gabbros and basalts, and is therefore also found in derived schistose types, glaucophane or sodic schists, with albite, epidote, muscovite.

Diag. Lawsonite differs from olivine in having better cleavages and weaker birefringence; it has stronger birefringence than zoisite or andalusite.

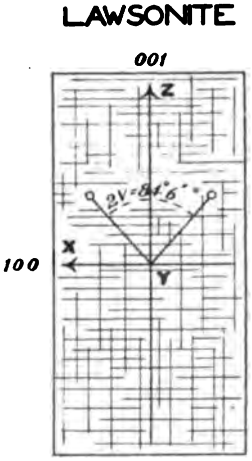

Fig. 138.
Optical orientation of lawsonite.

## LAZULITE.

Monoclinic $a:b:c::0.9749:1:1.6483$ $(Mg,Fe)(AlOH)_2(PO_4)_2$
$\beta = 89^\circ 14'$

Phys. Char. Crystals usually acute pyramidal in habit. Also massive. Twinning with *c* as the twinning axis. Indistinct prismatic cleavage. H. = 5.-6. G. = 3.0-3.12. Infusible, but whitens and crumbles when heated. Insoluble.

Opt. Prop. The plane of the optic axes is parallel to 010; the negative acute bisectrix makes an angle of 9°-10° with *c* in the acute angle $\beta$. The angle of the optic axes is large and the birefringence strong. Dispersion $\rho < v$ distinct, with slight inclined dispersion.

$$(-) \quad 2E = 132° - 136° \quad (2V = 69° \pm)$$

$$n_g = 1.639 \quad n_m = 1.632 \quad n_p = 1.603$$

$$n_g - n_p = 0.036$$

Color azure blue. Luster vitreous. In thin section pleochroism distinct with $Z = Y > X$, and Z azure blue, Y azure blue, X colorless.

Occur. Found in veins in quartzite and other metamorphic rocks. Rare.

Diag. Distinguished from corundum by its biaxial character and strong birefringence; from blue cordierite, sapphirine and dumortierite by its strong birefringence, from blue cyanite and blue amphibole by the absence of cleavage.

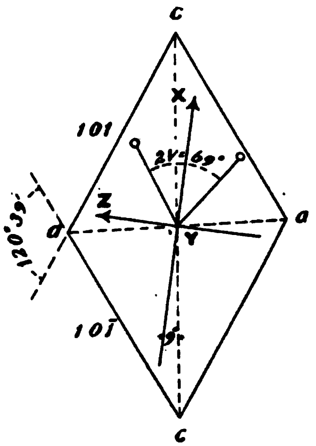

Fig. 139. Optical orientation of lazulite.

**LAZURITE**, see sodalite group.

## LEADHILLITE.

Monoclinic $\quad a:b:c::1.747:1:2.215 \quad (PbOH)_2Pb_2(CO_3)_2SO_4$

$$\beta = 89° \, 48'$$

Phys. Char. Crystals commonly tabular || 001, hexagonal in aspect. Twinning on 110 as in aragonite; also on 310 in lamellæ. Cleavage very perfect || 001, in traces || 100. H. = 2.5. G. = 6.26-6.44. Fusible with intumescence at 1.5. Effervesces in $HNO_3$ leaving $PbSO_4$ undissolved.

Opt. Prop. The optic plane is parallel to 010; the acute bisectrix X is sensibly normal to 001. Optic angle small; dispersion large $\rho < v$. The axial angle decreases with increase in temperature, and the mineral finally becomes uniaxial, negative, at 125°C. or more. At ordinary temperatures $2E = 20° - 23°$ Li. $n_g - n_p = 0.070$.

Color white, yellowish, green, gray. Streak colorless. Colorless in section.

Occur. Found in veins with lead and silver ores. Rare.

**Lanarkite** ($Pb_2SO_5$) is also monoclinic with $a:b:c::0.868:1:1.384$ and $\beta = 88° \, 11'$. Crystals elongated || *b*, tabular || 100. Cleavage perfect || 001. Laminæ flexible. H. = 2.-2.5. G. = 6.3-6.8. Partly soluble in $HNO_3$. Optic plane parallel to 010. Negative. Birefringence strong. $2H = 65° \, 3'$ Li; $2H = 63° \, 55'$ Tl. Found with caledonite. Very rare.

**LEPIDOLITE**, see mica group.

## LEUCITE.

Pseudo-isometric $KAlSi_2O_6$

Phys. Char. Usually in crystals very near the trapezohedron or tetragonal trisoctahedron in shape; 100 and 110 often present as modifying forms. Fine striations due to twinning common. Also granular, or massive. Cleavage || 110 indistinct. H. = 5.5-6. G. = 2.45-2.50. Infusible. Decomposed without gelatinization by HCl.

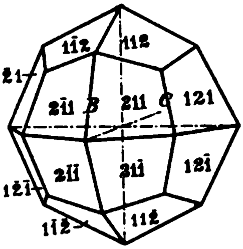

Fig. 140.
Simple crystal form of leucite.

Opt. Prop. Microscopically leucite is found to present very weak, but often distinct, birefringence. Much study of the subject has lead to the conclusion that all leucite crystallizes in the isometric system, but that it cannot remain isometric below 560°C.; therefore at ordinary temperatures it is only pseudo-isometric, and probably orthorhombic, the isometric form being composed of three interpenetrating orthorhombic crystals twinned on 110. The orthorhombic crystals have a very small optic axial angle about the positive bisectrix. The refringence is low.

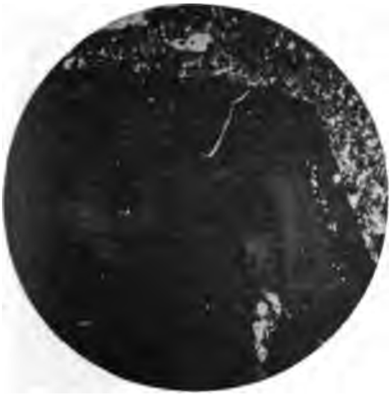

Fig. 141. Section of leucite showing very weak birefringence and complicated twinning, in leucitite from near Mt. Cimino, near Viterbo, Italy. H. 678. + nicols. × 10.

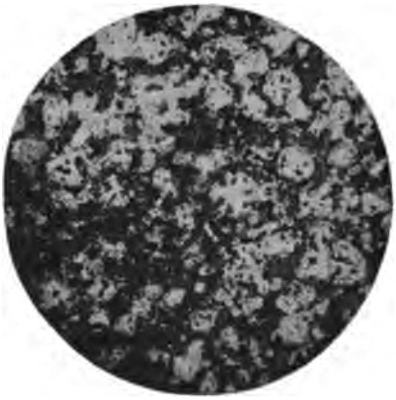

Fig. 142. Section of leucite crystals showing crystal form and regular inclusions, in leucitite from near Mt. Cimino, near Viterbo, Italy. H. 678. One nicol, × 50.

$$(+)\ 2V = \text{very small}$$

$$n_g = 1.509 \quad n_p = 1.508$$

$$n_g - n_p = 0.001$$

Colorless, white or gray. Colorless in thin section.

Incl. Leucite often contains inclusions (glassy, or of augite, or of magnetite, etc.) which are usually regularly arranged parallel to the faces of the enclosing crystal; sometimes radially arranged.

Alter. Leucite alters readily. In Tertiary and recent rocks the alteration product is commonly analcite (or christianite); in Paleozoic rocks the alteration product is commonly the so-called pseudo-leucite, which is a mixture of albite and sericite, orthoclase and sericite, or orthoclase and nepheline.

**Pollucite** is a very rare silicate $[H_2Cs_4Al_4(SiO_3)_9]$ related to leucite. Commonly in cubes, modified, or massive. Colorless. H. = 6.5. G. = 2.9. Isotropic. $n = 1.5247$ Na.

Diag. The low refringence, crystal form and twinning, and very weak birefringence, distinguish leucite from all minerals except analcite; it may be distinguished from analcite (and sodalite) by its higher refringence and by microchemical tests for potassium; if heated to redness analcite loses water and becomes opaque, while leucite remains unaltered.

## LEUCOPHANE.

Orthorhombic $a:b:c::0.9939:1:0.6722$ $Na(BeF)Ca(SiO_3)_2$

Phys. Char. Crystals commonly tabular || 001. Twinning frequent with 110 or 001 as twinning plane; interpenetration twins frequent. Massive in columnar or laminated forms. Crystals are pseudotetragonal and resemble meliphanite closely in axial ratio. Cleavage perfect || 001, distinct || 100 and 010, imperfect (parting) || 021 and 201. H. = 4. G. = 2.96. Fuses at 3 with intumescence to clear glass. Insoluble in acids.

Opt. Prop. The plane of the optic axes is parallel to 100; the negative acute bisectrix is normal to 001. Relief marked. Dispersion $\rho > v$.

$$(-)\ 2E = 74^\circ\ (2V = 39^\circ)$$

$$n_g = 1.5979 \quad n_m = 1.5948 \quad n_p = 1.5709$$

$$n_g - n_p = 0.027$$

Color white to green or yellow; in thin section colorless.

Occur. Found in pegmatite veins in syenite in Norway. Rare.

Diag. The optic properties with several cleavages are quite characteristic. Chemically distinguished by giving reactions of Be and F.

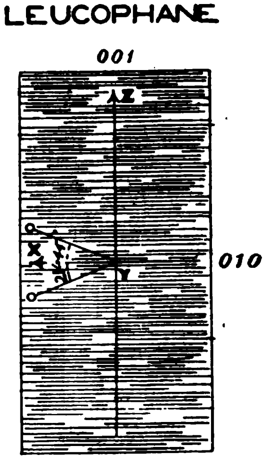

Figure 143.
Optical orientation of leucophane.

## LEUCOSPHENITE.

Monoclinic $a:b:c::0.581:1:0.850$ $BaNa_4(TiO_2)(Si_2O_5)_5$?

$\beta = 86° 37'$

Phys. Char. Crystals elongated || $c$ or flattened || 001; often twinned on 001. Cleavage distinct || 010. H. = 6.5. G. = 3.05. Difficultly fusible with decrepitation. Decomposed by HF.

Opt. Prop. The optic plane is nearly parallel to 001; the acute bisectrix X is nearly parallel to $a$; $Y \wedge c = +3°$. Dispersion $\rho > v$ strong. Color white.

$$(-)\ 2V = 77° 4'$$
$$n_g = 1.687 \quad n_m = 1.6609 \quad n_p = 1.6445$$
$$n_g - n_p = 0.0433$$

Occur. Found in southern Greenland. Very rare.

**LIBETHENITE,** see olivenite.

## LIMONITE.

Orthorhombic Axial ratio unknown. $Fe_4(OH)_6O_3$

Phys. Char. Crystals unknown; commonly in botryoidal, mammillary or stalactitic forms with fibrous texture; also concretionary, massive, earthy. Fibers elongated || $c$, and radially arranged, in stalactites. Cleavage || 100. H. = 5.-5.5. G. = 3.6-4. Yields $H_2O$ in closed tube. Soluble in HCl.

Opt. Prop. The plane of the optic axes is parallel to the cleavage 100; the negative acute bisectrix is normal to 010. Refringence very high; birefringence very strong. Optic angle large; dispersion $\rho > v$ strong, but not abnormal as in goethite.

$$(-)\ 2V = \text{large.}$$
$$n = 2.5 \pm$$
$$n_g - n_p = 0.048$$

Color yellow, brown, brownish black; often iridescent on the exterior. Streak yellowish brown. Luster silky and submetallic to earthy. Translucent only in thin section with distinct pleochroism, the absorption being Y>Z>X, and the colors Z orange yellow, Y brownish yellow, X clear yellow.

Incl. Inclusions of quartz, kaolinite, manganite, etc., are abundant, and explain at least in part the variations in analyses.

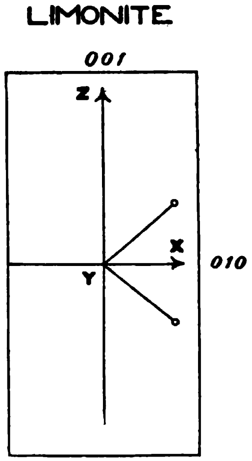

Figure 144.
Optical orientation of limonite.

ALTER. By dehydration limonite passes to hematite. *Turgite* ($2Fe_2O_3 \cdot H_2O$) is perhaps merely an incomplete stage in this process. Limonite is a common result of oxidation and hydration of ferruginous minerals.

OCCUR. Limonite is extremely common as an alteration product of ferriferous minerals. It is found in all kinds of igneous and metamorphic rocks; it is formed in the upper part of nearly all veins, and is deposited by some hot springs occasionally in sufficient abundance to serve as an ore deposit. In sedimentary rocks limonite is also abundant, sometimes serving as an ore. It also forms in swamps as a bog iron ore. Native iron changes rapidly to limonite when exposed in most climates. Limonite is common in submicroscopic particles, staining other minerals.

DIAG. Limonite differs from goethite optically in its large optic angle, and in the absence of abnormal dispersion, and from lepidocrocite in its pleochroic formula, and in having the maximum absorption normal to the elongation.

## LINARITE.

MONOCLINIC $a:b:c::1.716:1:0.830$ $(Pb,Cu)(OH)_2(Pb,Cu)SO_4$
$\beta = 77° 23'$

PHYS. CHAR. Crystals elongated || *b*, often tabular || 001. Cleavage very perfect || 100, imperfect || 001. H. = 2.5. G. = 5.3-5.45. Fuses easily to a globule reducible to metal. Partly soluble in $HNO_3$.

OPT. PROP. The optic plane and obtuse bisectrix Z are normal to 010; X makes an angle of —24° with 001, therefore it is nearly normal to $\bar{1}01$. Optic angle large; dispersion $\rho < v$ marked.

$$(-)\ 2V = 79° 59'$$
$$n_g = 1.8593 \quad n_m = 1.8380 \quad n_p = 1.8092$$
$$n_g - n_p = 0.050.$$

Color deep azure blue. Streak pale blue. Luster vitreous or adamantine.

ALTER. Sometimes alters to cerussite.

OCCUR. Found in veins in lead mines. Rare.

## LIROCONITE.

MONO. $a:b:c::1.319:1:1.681$ $Cu_9Al_4(OH)_{15}(AsO_4)_5 + 20H_2O$
$\beta = 88° 33'$

PHYS. CHAR. Crystals thin, rhombic octahedral in aspect; rarely granular. Cleavage indistinct || 110 and 011. H. = 2.-2.5. G. = 2.88-2.98. Fusible; deflagrates on charcoal. Soluble in $HNO_3$.

OPT. PROP. The optic plane and acute bisectrix X are normal to 010; Z makes an angle of — 25° with *c*. Optic angle large; dispersion $\rho < v$.

(—) $2E = 132° 57'$ Na.

Color and streak sky blue to verdigris green. Luster vitreous inclining to resinous.

OCCUR. Found in veins with copper ores, pyrite, quartz, etc Rare.

**LITHIOPHILITE**, see triphylite.

## LORENZENITE.

ORTHORHOMBIC $a:b:c::0.604:1:0.359$ $Na_2(Si,Ti,Zr)_8O_9$

PHYS. CHAR. Crystals prismatic, elongated || $c$. Cleavage distinct || 120. H. = 6. G. = 3.42. Easily fusible. Insoluble except in HF.

OPT. PROP. The optic plane is parallel to 100; the acute bisectrix Z is normal to 010. Color brownish. Luster adamantine. In section colorless to pale brown or violet brown with absorption $Y > Z > X$. (+) $2E = 72°$. $n_g = 1.7876$, $n_m = ?$ $n_p = 1.7431$; $n_g - n_p = 0.0445$.

OCCUR. Found in southern Greenland. Very rare.

## LOEWEITE.

TETRAGONAL $c = ?$ $Na_2Mg(SO_4)_2 + 2\frac{1}{2}H_2O$

PHYS. CHAR. Massive, cleavable. Cleavage distinct || 110, in traces || 111. H. = 2.5-3. G. = 2.37. Soluble in $H_2O$.

OPT. PROP. Uniaxial and positive. Refringence low; $n_g = 1.494$, $n_p = 1.491$; $n_g - n_p = 0.003$.

Color nearly white to yellow, reddish. Luster vitreous.

OCCUR. Found in salt mines. Very rare.

**Blödite** [$Na_2Mg(SO_4)_2 + 4H_2O$] is monoclinic with $a:b:c::1.349:1:0.670$, and $\beta = 79° 22'$. Crystals short prismatic. Also massive granular or fibrous. Cleavage unknown. H. = 2.5. G. = 2.22-2.28. Fusible. Soluble in $H_2O$. Somewhat deliquescent. Optic plane parallel to 010; acute bisectrix Z makes an angle of $-45°$ with $c$. Inclined dispersion, with $\rho < v$ marked. $2V = 70° 5'$ Li; $n_m = 1.500$. Colorless to bluish green, reddish yellow, brick red. Luster vitreous. Found in salt mines. Rare.

## LUDLAMITE.

MONOCLINIC $a:b:c::2.252:1:1.982$ $Fe(OH)_2Fe_5(PO_4)_2 + 8H_2O$
$\beta = 79° 27'$

PHYS. CHAR. Crystals tabular || 001. Cleavage perfect || 001, indistinct || 100. H. = 3.-4. G. = 3.12. In closed tube decrepitates and gives off water. Soluble in HCl.

OPT. PROP. The optic plane is parallel to 010; the acute bisectrix Z makes an angle of $-67°$ with $c$. Inclined dispersion very slight with $\rho > v$ weak. $2V = 82° 22'$.

Color bright green; streak pale greenish. Luster vitreous, brilliant.

OCCUR. Found with siderite, vivianite, pyrite. Very rare.

**MAGNESIOFERRITE,** see spinel group. **MAGNESITE,** see calcite group. **MAGNETITE,** see spinel group.

## MALACHITE.

MONOCLINIC $a:b:c::0.881:1:0.401$ $(CuOH)_2CO_3$

$\beta = 61° 50'$

PHYS. CHAR. Crystals usually acicular prisms grouped in tufts; distinct forms rare; commonly massive, botryoidal, stalactitic with fibrous textures; also granular, earthy. Twinning on 100 common. Cleavage perfect || 001, imperfect || 010. H. = 3.5-4. G. = 3.9-4. Fusible at 2 with green flame color. Soluble with effervescence.

OPT. PROP. The plane of the optic axes is parallel to 010; the acute bisectrix X makes an angle of 23½° with *c*, or 85° with the cleavage 001. Refringence high. Birefringence extremely strong. Optic angle large.

$(-)\ 2V = 43° 54'$ Na $(2E = 89° 18'$ Na$)$

$n_m = 1.88$ Na

$n_g - n_p = 0.200$

Color bright green. Streak paler green. Luster adamantine, silky, or earthy.

OCCUR. Common with copper ores as a product of surface weathering. Found both in veins and disseminated. Especially abundant where copper veins penetrate limestone, or have a calcite gangue.

DIAG. Differs from atacamite in having inclined extinction in the vertical zone, and in extremely strong birefringence.

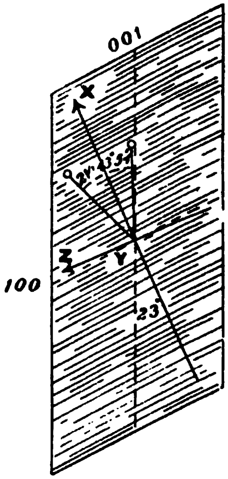

Figure 145.
Optical orientation of malachite.

**MANGANITE,** see diaspore group.

## MARCASITE.

ORTHORHOMBIC $a:b:c::0.766:1:1.234$ $FeS_2$

PHYS. CHAR. Crystals tabular || 001, or pyramidal. More commonly in masses of various shapes with radiating or fibrous texture. Twinning on 110, sometimes repeated; twinning on 101 less common. Cleavage distinct || 110, in traces || 011. H. = 6.-6.5. G. = 4.85-4.90. On charcoal burns with sulphurous odor. Decomposed by $HNO_3$.

Opt. Prop. Opaque. Color pale bronze yellow. Streak grayish or brownish black. Luster metallic. Polishes with difficulty.

Alter. Alters by oxidation much more rapidly than pyrite, and gives rise to melanterite, or, less commonly, copiapite. At the same time free sulphuric acid is produced, which is an active agent in some of the processes of secondary enrichment of ore deposits. At other times marcasite alters to limonite, or göthite, or hematite, sometimes with the production of free sulphur.

Occur. Found abundantly in clay in coal formations; in metalliferous veins in all kinds of rocks with copper, lead, zinc, etc.; in veins and disseminations in limestones; also in some igneous and metamorphic rocks, and in pegmatite veins.

**Arsenopyrite** or **mispickel** (FeAsS) is also orthorhombic with $a:b:c::0.677:1:1.188$. Crystals prismatic or modified. Also in columnar or radiated groups; massive granular. Twinning like marcasite. Cleavage distinct || 110. H. = 5.5-6. G. = 5.9-6.2. Strikes fire with steel giving an alliaceous odor. Decomposed by $HNO_3$. Opaque. Color silver white, somewhat grayish. Streak dark grayish black. Luster metallic. Found especially in veins, commonly associated with ores of silver, lead, tin, gold; also found in crystalline rocks, and in serpentine.

## MARGARITE.

Monoclinic Axial ratio near that of biotite. $H_2CaAl_4Si_2O_{12}$

Phys. Char. Crystals rare; in thin six-sided plates; commonly in thin lamellar aggregates, or scaly masses. Twinning on the mica law common. Cleavage micaceous || 001; the laminæ are brittle and inelastic. Gives a percussion figure like that of mica. H. = 3.5-4.5. G. = 2.99-3.08. Fuses on the edges after turning white. Imperfectly decomposed by hot $H_2SO_4$.

Opt. Prop. The plane of the optic axes is normal to 010; the negative acute bisectrix makes an angle of about 6° with a normal to 001; this angle is somewhat variable. The angle of the optic axes is quite variable; axial dispersion $\rho < v$.

$$(-)\ 2E = 80° - 125°$$
$$n_m = 1.64 - 1.65$$
$$n_g - n_p = 0.009 \pm$$

Color grayish, reddish, white, pink, yellowish; colorless in thin section.

Alter. Margarite alters to a brownish yellow hydrous micaceous mineral known as *dudleyite*.

Occur. Margarite is found in metamorphosed and altered rocks associated with corundum, from which it is often derived. Also found in mica schist with tourmaline and staurolite.

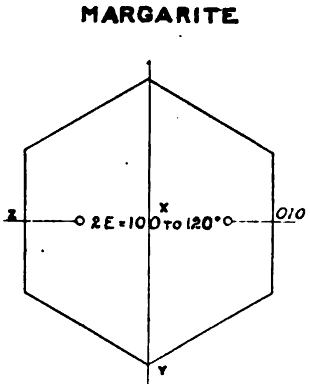

Figure 146.
Optical orientation of margarite.

Diag. Margarite differs from the micas in its much weaker birefringence; it is distinguished from chloritoid and chlorite by the absence of color in thin section.

**MARIALITE,** see scapolite group.

## MARSHITE.

ISOMETRIC $Cu_2I_2$

PHYS. CHAR. Crystals minute, tetrahedral. Cleavage || 110. H. = 2.5.

OPT. PROP. Isotropic. Refringence extremely high, $n = 2.346$ Na. Dispersion greater than that of the diamond. Color wine yellow to brick red. Streak orange yellow. Luster adamantine.

OCCUR. Found with cerussite or anglesite. Very rare.

**Miersite** ($Ag_2I_2$) is like marshite, in minute cubes of pale to bright yellow color. Cleavage || 110. Twins on 111. Isotropic. Found with chalcocite, etc. Very rare.

**MEIONITE,** see scapolite group.

## MELANTERITE.

MONOCLINIC $a:b:c::1.183:1:1.543$ $FeSO_4 + 7H_2O$

$\beta = 75° 44\frac{1}{2}'$

PHYS. CHAR. Natural distinct crystals unknown. Commonly fibrous, capillary, stalactitic; massive, pulverulent. Cleavage perfect || 001, imperfect || 110. H. = 2. G. = 1.89-1.90. Soluble in $H_2O$; taste astringent.

OPT. PROP. The optic plane is parallel to 010; the acute bisectrix Z makes an angle of $-61°$ with $c$. Refringence low. Inclined dispersion weak with $\rho > v$.

$$(+)\ 2V = 86° 13'$$
$$n_m = 1.470$$

Color green to white, becomes yellow by alteration to copiapite. Luster vitreous. Streak colorless.

OCCUR. Produced by atmospheric alteration of marcasite and pyrite. Rare.

**Pisanite** [$(Fe,Cu)SO_4 + 7H_2O$] is monoclinic with $a:b:c::1.161:1:1.511$, and $\beta = 74° 38'$. Usually in stalactites and concretions. Cleavage easy || 001. Soluble in $H_2O$. Optic plane parallel to 010; acute bisectrix Z nearly parallel to $a$; X nearly perpendicular to the perfect cleavage 001. $2H_a = 85° 52'$ Na. Color bright blue. Luster vitreous. Found in copper mines. Very rare.

**Boothite** ($CuSO_4 + 7H_2O$) is monoclinic with $a:b:c::1.162:1:1.500$ and $\beta = 74° 24'$. Usually fibrous. Cleavage perfect || 001. H. = 2.5. G. = 2.1. Soluble in $H_2O$. Unstable under ordinary conditions. Optic plane parallel to 010; acute bisectrix Z nearly parallel to $a$; X nearly perpendicular to perfect cleavage 001. Color blue. Found in copper mines. Very rare.

**Melilite Group.**

The minerals of this group are silicates crystallizing in the tetragonal system. They are all more abundant in furnace slags than in nature, and the last named is unknown except in slags.

| | | |
|---|---|---|
| Gehlenite | $c = 0.4000$ | $Ca_3Al_2Si_2O_{10}$ or $Ca_3AlAlSi_2O_{10}$ |
| Melilite | $c = 0.4548$ | $mCa_3AlAlSi_2O_{10} + nCa_3CaSiSi_2O_{10}$ |
| Åkermanite | $c = 0.45 \pm$ | $Ca_4Si_3O_{10}$ or $Ca_3CaSiSi_2O_{10}$ |

The composition is given above in the second way to show the relation between the formula of gehlenite and that of åkermanite. Vogt considers them isomorphous and considers that the groups CaSi and AlAl may replace each other in any proportions. Furthermore, since gehlenite is negative and åkermanite is positive, their combination in a certain proportion should lead to an isotropic mineral. This proportion according to Vogt is four parts of gehlenite to six parts of åkermanite.

It should be remarked that the formulas given above are simplified as much as possible. The bivalent base is often partly replaced by Mg. $Na_2$, Mn, Fe or $K_2$, while the trivalent base is often partly replaced by Fe.

## GEHLENITE.

Tetragonal $c = 0.40006$ $Ca_3Al_2Si_2O_{10}$

Phys. Char. Crystals usually short square prisms; basal cleavage imperfect, and cleavage in traces parallel to the prism. H. = 5.5-6. G. = 2.9-3. Fuses with difficulty. Gelatinizes with HCl.

Opt. Prop. Uniaxial and negative. Usually rectangular in sections.

$$n_g = 1.663 \quad n_p = 1.658$$
$$n_g - n_p = 0.005\text{-}0.006$$

Color grayish green to liver brown; colorless in thin section.

Alter. Alters to steatite, to augite, to grossularite.

Occur. Rare in nature. Found at Mt. Monzoni as a contact mineral in limestone.

Diag. Resembles vesuvianite and zoisite, but zoisite is biaxial and positive, while vesuvianite has higher refringence and weaker birefringence.

## MELILITE.

Tetragonal $c = 0.4548$ $mCa_3Al_2Si_2O_{10} + nCa_4Si_3O_{10}$

Phys. Char. Usually in short square or octagonal prisms; sometimes lamellar parallel to the base. Cleavage perfect parallel to the base, very difficult parallel to a prism. Cruciform twins rare in which the vertical axes are at right angles. H. = 5.-5.5. G. = 2.9-3.1. Fuses at 3. Gelatinizes with HCl.

Opt. Prop. Native melilite is uniaxial and negative. It usually approximates the composition of four parts of gehlenite and three parts of åkermanite. According to Vogt, as the proportion of åkermanite increases the birefringence decreases until it disappears, and the mineral is then isotropic. Further increase leads to the reappearance of the birefringence in a positive uniaxial mineral. Such wide variations of composition are found only in slags.

$$n_g = 1.6339 \quad n_p = 1.6291$$
$$n_g - n_p = 0.005 \text{ (average)}$$

Color white, yellow, brown; colorless to yellow in thin section.

INCL. Native melilite often contains cuneiform inclusions arranged normal to the base, which are perhaps alteration products. Artificial melilite often shows vitreous or crystalline inclusions regularly arranged.

OCCUR. Found rarely in basic nepheline and leucite rocks as an accessory constituent; also rarely as an essential constituent of melilite basalts. Also in furnace slags.

**Åkermanite** is similar to melilite in crystal form and physical characters; it is known only as a product of crystallization from furnace slags in which it occurs in thin tabular crystals with cleavage parallel to 110 and perhaps also to 001. Åkermanite is positive with weak birefringence.

DIAG. The high refringence with very weak birefringence and lack of color are distinguishing characters. When the cuneiform inclusions are present they are quite characteristic.

## MELIPHANITE.

TETRAGONAL $c = 0.658$ $NaCa_2Be_2FSi_3O_{10}$

PHYS. CHAR. Crystals often obtuse pyramids; also in plates or lamellar masses. Cleavage || 001 distinct. H. = 5.-5.5. G. = 3.00-3.02. Fuses with intumescence to a white enamel. Insoluble in acids.

OPT. PROP. Uniaxial and negative. Colorless in thin section. Relief marked. Birefringence strong. The interference figure is sometimes normal, sometimes distorted, and the cross opens a variable amount, reaching at times $2E = 36°$. A single plate may show normal and abnormal interference figures in different parts.

$$n_g = 1.6126 \quad n_p = 1.5934$$
$$n_g - n_p = 0.0192$$

Color yellow, orange; rarely reddish, usually due to alteration. Pleochroism visible only in thick plates, with absorption $Z > X$, and Z honey to brownish yellow, X greenish yellow.

OCCUR. Found in pegmatite veins in alkaline syenites of southern Norway. Rare.

DIAG. Distinguished from hiortdahlite, wöhlerite and låvenite by uniaxial (or, abnormally, biaxial with small optic angle) character and insolubility in acids; distinguished from leucophane by the lack of color and poor cleavage.

**MELLITE.**

TETRAGONAL $c = 0.746$ $Al_2C_{12}O_{12} + 18H_2O$

PHYS. CHAR. Crystals pyramidal; massive granular. Cleavage in traces || 111. H. = 2.-2.5. G. = 1.55-1.65. Soluble in $HNO_3$.

OPT. PROP. Negative; uniaxial; sometimes abnormally biaxial with $2E = 8° 22'$ Li. Birefringence strong. $n_g = 1.539$; $n_p = 1.511$; $n_g - n_p = 0.028$. Color honey yellow; also brownish, reddish, white. Streak white. Luster resinous.

OCCUR. Found in brown coal. Rare.

**MESOLITE,** see zeolite group.

**Mica Group.**

The mica group includes several minerals which are monoclinic and pseudohexagonal (or pseudorhombohedral); they are further characterized by a perfect basal cleavage giving thin elastic laminæ; optically they are characterized by weak birefringence in sections perpendicular to the perfect cleavage.

PHYS. CHAR. Crystals of all the micas are commonly thin plates of hexagonal outline, with the planes 001, 110, $1\bar{1}0$, and 010. In all of them the angle $001 \wedge 100$ is very near 90° and the angles $110 \wedge 1\bar{1}0$ and $110 \wedge 010$ are very near 60°. A blow with a dull point on a cleavage plate of any mica develops a six-rayed percussion figure, one line being more distinct than the other two. (See figure 147). This line is parallel to 010, while the other two are parallel to 110 and $1\bar{1}0$. This figure makes it possible to determine the position of 010 in any cleavage piece of mica, even though no crystal faces are present. Pressure, instead of a blow, on a cleavage plate of mica, produces a six-rayed pressure figure whose lines are perpendicular to those of the percussion figure. H. = 2.5-4. G. = 2.75-3.2.

Twinning is common in all the micas. The twinning plane in the "mica law" is a plane normal to 001 and practically parallel to 110; the composition face may be 110 or 001, or the twins may combine irregularly.

The micas give water in the closed tube; they are fusible before the blowpipe; the ferromagnesian micas are attacked by acids, leaving a skeleton of silica; other micas are nearly or quite insoluble.

OPT. PROP. In all the micas the negative acute bisectrix is almost exactly perpendicular to the basal cleavage 001, so that cleavage laminæ show a bisectrix. The plane of the optic axes is parallel or perpendicular to 010, varying in different species. The percussion figure makes it possible to determine the position

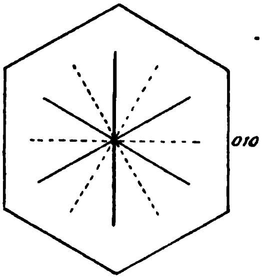

**Figure 147.**
Percussion figure (in full lines) and pressure figure (in dotted lines) of the micas.

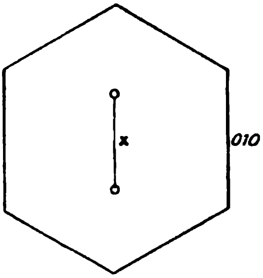

**Figure 148.**
Optical orientation of biotite, phlogopite, and zinnwaldite.

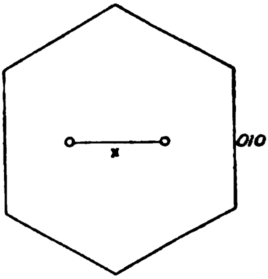

**Figure 149.**
Optical orientation of muscovite, paragonite, lepidolite and anomite.

of the optic plane with reference to 010 even though no crystal face be present. (See figures 147-149). The ferromagnesian micas are usually very nearly uniaxial; other micas usually have a larger angle of the optic axes.

The birefringence of the micas is always very strong, varying from 0.04 to 0.05. The refringence always produces distinct relief in the micas. Absorption is very strong in the colored micas.

The dispersion is $\rho > v$ and the optic plane is normal to 010 in muscovite, paragonite, lepidolite, and anomite; the dispersion is $\rho < v$ and the optic plane is parallel to 010 in biotite, phlogopite, and zinnwaldite.

The micas vary in color in the different varieties, being colorless, white, gray, yellow, brown, green, black, pink, violet. Luster vitreous to pearly.

Diag. In thin sections micas are characterized by distinct relief, strong birefringence (chlorites and clintonites have weak birefringence), optic orientation, one perfect cleavage marked by fine parallel lines, practically parallel extinction, the mottled appearance between crossed nicols, and in colored varieties maximum absorption parallel to the vibration plane of the lower nicol.

The species of the mica group may be classified as follows:

| | | | |
|---|---|---|---|
| Paragonite | | | $H_2(Na,K)Al_3(SiO_4)_3$ |
| Muscovite | $a:b:c::0.577:1:3.313$ | $\beta = 89° 54'$ | $H_2(K,Na)Al_3(SiO_4)_3$ |
| Lepidolite | | | $(F,OH)_2(Li,K,Na)_2Al_2Si_3O_9$ |
| Zinnwaldite | | | $(F.OH)_2(Li.K.Na)_3FeAl_3Si_5O_{16}$ |
| Phlogopite | | | $(K,H)_3(MgF)_2Mg_3Al(SiO_4)_3$ |
| Biotite | $a:b:c::0.577:1:3.274$ | | $(K,H)_2(Mg,Fe)_2(Al,Fe)_2(SiO_4)_3$ |
| Anomite | $\beta = 90° 0'$ | | |

The composition of the micas is very complex, and not yet fully worked out; the formulas given above are, in part, only approximate, and in part only correct for some varieties. Anomite is distinct optically from biotite, but the chemical differences are not certainly known; Tschermak assigns to anomite a formula in which K is in excess over basic H, while he assigns to biotite formulas in which the basic H is equal or in excess over the K.

## PARAGONITE.

MONOCLINIC (PSEUDOHEXAGONAL) $H_2(Na,K)Al_3(SiO_4)_3$

PHYS. CHAR. Usually massive in very fine scales; also compact. Perfect basal cleavage. H. = 2.5-3. G. = 2.78-2.90. Gives little water in the closed tube. Difficultly fusible. Some varieties (*pregrättite*) exfoliate when heated, like vermiculite, and become milky white on the edge. Insoluble in acids.

OPT. PROP. The plane of the optic axes is normal to 010; the negative acute bisectrix is very nearly normal to 001. Relief distinct; birefringence very strong. Dispersion $\rho > v$.

$$n = 1.60$$

Color white, grayish or greenish white, yellow. Luster pearly. Absorption not marked. $Z = Y > X$. Colorless in thin section.

OCCUR. Found in masses in some crystalline schists. It is possible that many of the white micas formed by alteration processes from nepheline, albite, and other soda minerals. may be paragonite; they are usually considered to be sericite (variety of muscovite), but paragonite and muscovite cannot be distinguished optically.

DIAG. Distinguished from talc by the large optic angle; only distinguishable from muscovite and lepidolite by chemical tests. Rare.

## MUSCOVITE.

MONOCLINIC (PSEUDOHEXAGONAL) $H_2(K,Na)Al_3(SiO_4)_3$

$$a:b:c::0.577:1:3.313$$

$$\beta = 89° 54'$$

PHYS. CHAR. Crystals usually tabular with hexagonal outline, sometimes tapering. More commonly in lamellar masses; also cryptocrystalline massive. Twinning on the mica law not rare. Perfect basal cleavage yielding thin elastic lamellæ; also secondary cleavage or parting parallel to 010, and to several unit pyramids as shown in the percussion figure. H. = 2.5-3. G. = 2.76-3. In closed tube gives water, and often fluorine. Fusible at 5.7 to gray or yellow glass. Not attacked by acids.

OPT. PROP. The plane of the optic axes is normal to 010; the negative acute bisectrix X makes an angle of 0° to 2° with a normal to the base. The angle of the optic axes is about 70° ($2E$); it is less in muscovite rich in silica, and much less in muscovites slightly altered (sericite, damourite). In these the angle may decrease nearly to 0°. The relief is distinct and the birefringence very strong. Dispersion $\rho > v$.

$$(-)2E = 70° \text{ (average) } 60° \text{ to } 75°$$
$$n_g = 1.5977 \quad n_m = 1.5936 \quad n_p = 1.5601$$
$$n_g - n_p = 0.0376$$

In many cases twinning lamellæ are so superposed that only the very thinnest cleavage scales are homogeneous in orientation.

Colorless, gray, brown, pale green, etc. Luster vitreous to pearly. Streak colorless. In thin section colorless, except in some pleochroic halos. But in thick plates and in the halos of thin sections distinctly pleochroic, with Z = Y > X, and

Z = Y = pale yellow to brown.
X = colorless.

INCL. Zircon crystals are sometimes found as inclusions; they often produce pleochroic halos even in otherwise colorless muscovite. Other minerals sometimes present include apatite, spinel, garnet, tourmaline, quartz, and magnetite or hematite, the last in dendritic forms.

ALTER. In deep seated rocks muscovite is stable; in surface rocks it may weather chiefly by hydration, and thus change to damourite ("hydromica," sericite, etc.), serpentine minerals, or talc. In case of change to talc hydrargillite probably forms at the same time. Muscovite may also alter to paragonite.

**Damourite** is a slightly altered muscovite in which the water is either increased or becomes less closely combined than in muscovite. The cleavage laminæ are flexible, but lose their elasticity as the change progresses. At the same time the angle of the optic axes decreases from 70° to a minimum nearly uniaxial. Thus, the damourite of Pontivy, France, has $2E = 10°$ to 12°.

**Sericite** is a fine scaly or fibrous kind, of damourite; the name is also sometimes applied to unaltered muscovite.

OCCUR. Muscovite is the most common of the micas. It is a normal constituent of many igneous rocks, especially the granites. It is an important constituent of gneiss and micaschist and various related rocks. It occurs in large crystals in veins and dikes, especially in pegmatite. It occurs in various rocks, also, as a decomposition product, being derived from many sources, as, feldspar, nephelite, scapolite, spodumene, cordierite, cyanite, topaz, etc. It occurs sparingly in sedimentary and fragmental rocks, but metamorphism may develop it in these rocks.

**Fuchsite** is a variety of muscovite containing $Cr_2O_3$, replacing $Al_2O_3$ (to 4%). In fuchsite $2E = 68°-70°$ with $\rho > v$. Fuchsite is green with distinct pleochroism as follows: Z = Y = green; X = colorless. In thick sections Z = dark bluish green; Y = yellowish green; X = pale greenish blue. Fuchsite is found in micaceous quartzites, mica-schists, and sparingly in gneisses and dolomites.

**Leverriérite** is a hydrous aluminum silicate considered by some writers a variety of kaolinite, by others a variety of mica. It has twinning on the mica, and also other, laws; micaceous cleavage. H. = 1.5. G. = 2.6. Occurs in vermicular forms which have been mistaken for organisms and called bacillarites. The plane of the optic axes is parallel to 010, and the negative acute bisectrix very nearly normal to 001, the basal cleavage. $2V = 0°-50°$, varying even in a single lamella, usually about uniaxial. $n_g$ nearly $= n_m = 1.582$; $n_p = 1.554$; $n_g - n_p = 0.028$. Leverriérite contains a brown (organic?) pigment. Pleochroism distinct in thin section with Z = clear brown; Y = dark brown; X = colorless. Leverriérite is common in black carbonaceous shales in parts of France; also found in porphyry.

**Chromocre** is probably a cryptocrystalline variety of muscovite very rich in chromium. It occurs in earthy or granular masses of minute globules with lamellar texture. Cleavage perfect || 001. H. = 1. G. = 2.47. Insoluble in acids. The acute bisectrix X is normal or nearly normal to the cleavage 001. The optic angle is very small. Color apple green to dark green. Pleochroism weak and variable in thin section with Z = Y bright green, X yellowish green to colorless. Found in slates and quartz veins. Differs from glauconite in its brighter green color and presence of chromium.

Diag. Muscovite is distinguished from pale phlogopite by the position of the optic plane, from talc by the large optic angle, and from kaolinite, chlorite, etc. by the strong birefringence. Distinguished from lepidolite and paragonite only by chemical tests.

## LEPIDOLITE.

Monoclinic $(Li,K)[Al(F,OH)_2]Al(SiO_3)_3$

Phys. Char. In aggregates of short prisms, or, more commonly, in lamellar aggregates more or less compact. Micaceous cleavage || 001. Twinning on the mica law. H. = 2.5-4. G. = 2.8-2.9. In the closed tube gives water and fluorine. Fusible at 2.5 with intumescence. Incompletely decomposed by acids.

Opt. Prop. The plane of the optic axes is normal to 010*; the negative acute bisectrix is very nearly normal to 001. Relief perceptible; birefringence very strong. The angle of the optic axes is quite variable. Dispersion $\rho > v$; also crossed dispersion.

---

* W. T. Schaller (*Bull.* 262. *U. S. G. S.*) describes lepidolite from California having the optic plane parallel to 010.

$$(-)\ 2E = 57°\text{-}83°.$$

$$n_g = 1.6047 \quad n_m = 1.5975 \quad n_p = 1.56\pm$$

$$n_g - n_p = 0.037\ \pm$$

Color pink, red, violet, yellow, gray, colorless. The common pink color is supposed to be due to traces of manganese. Luster pearly. Colorless in thin section; in thick sections distinct pleochroism, as follows:—

Z = Y = pink.
X = colorless.

Occur. Found exclusively in veins and pegmatite dikes in granite, gneiss, etc., often associated with cassiterite, tourmaline, amblygonite, spodumene, etc. Often found in parallel growths with muscovite.

Diag. Microscopically indistinguishable from muscovite and paragonite. Megascopically, the pink color is often distinctive; further, the fusibility, and the reaction for lithium.

## ZINNWALDITE.

Monoclinic (Pseudohexagonal) $(F,OH)_2(Li,K,Na)_2FeAl_3Si_5O_{16}$

Phys. Char. Crystals often in fan-shaped groups or rosettes; more commonly in isolated or aggregated lamellæ. Very similar to biotite. Micaceous cleavage || 001. Twinning on the mica law. H. = 2.5-3. G. = 2.8-3.2. Fusible at 1.5-2 to black glass. Gives water and fluorine in the closed tube. When finely powdered completely soluble in acids.

Opt. Prop. The plane of the optic axes is parallel to 010; the negative acute bisectrix is very nearly normal to 001; $X \wedge c = 0°\text{-}7°$. Relief marked; birefringence very strong. Angle of optic axes variable in different varieties. Dispersion $\rho < v$ weak.

$$(-)\ 2V = 10°\text{-}60° \quad 2E = 50°\text{-}65° \text{ usually.}$$

Color pale violet, yellow, gray, brown; in thin section pleochroic with absorption Z > Y > X, and pleochroism as follows:—

| | Dark varieties. | Light colored varieties. |
|---|---|---|
| Z = | dark brown | brownish gray |
| Y = | dark brown | brownish gray |
| X = | yellowish brown or reddish | nearly colorless |

Incl. Rutile, zircon, cassiterite and topaz often occur as inclusions, usually surrounded by pleochroic halos.

Occur. Found in veins in granite with tin ores, topaz, etc. Also in pegmatitic veins in other rocks, as syenite, gneiss, etc. Rare.

*Cryophyllite, polylithionite,* and *irvingite*[1] are varieties of zinnwaldite or lepidolite characterized by low alumina and somewhat variable proportions of the alkalies. Cryophyllite is pleochroic in thin section with Z = Y brownish red, X emerald green.

Diag. Distinguished from lepidolite (also muscovite and paragonite) by the position of the optic plane. The optic angle is usually much larger than in biotite or phlogopite, but a chemical test for lithium is more conclusive.

---

[1] S. Weidman, *G. N. H. S. Wis. Bull.* XVI. p. 297.

## PHLOGOPITE.

Mono. (Pseudohexagonal) $(K,H)_3(MgF)_3Mg_3Al(SiO_4)_3$

Phys. Char. Crystals often large and coarse; usually in six-sided prisms, very short. Similar to biotite. Micaceous cleavage || 001. Twinning on the mica law. H. = 2.5-3. G. = 2.78-2.85. Fuses on the thin edges after turning white. Completely decomposed by sulphuric acid leaving scales of silica.

Opt. Prop. The plane of the optic axes is parallel to 010; the negative acute bisectrix is very nearly normal to 001. Relief marked; birefringence very strong. Angle of the optic axes small, but variable even in a single crystal. Dispersion $\rho < v$.

$$(-)\ 2E = 0° - 30°$$

$$n_g = 1.606 \text{ approx.} \quad n_m = 1.606 \quad n_p = 1.562$$

$$n_g - n_p = 0.044$$

Color yellowish brown, brownish red, green, yellow, colorless; usually pleochroic in thin section, with Z > Y > X, and

Z = Y = brownish yellow
X = colorless

Incl. Inclusions are common, and they cause asterism on account of their arrangement along lines at about 60° apart. They consist of hematite or rutile, or tourmaline, or an unknown mineral of low relief and strong birefringence.

Occur. Phlogopite seems to be found only in crystalline limestones, dolomites, and serpentines. Absent or very rare in igneous rocks.

Diag. Phlogopite is distinguished from muscovite, paragonite and lepidolite by color, and the position of the optic plane. Differs from zinnwaldite usually in its smaller optic angle, and from zinnwaldite and biotite in its mode of occurrence; but chemical tests to show the relative absence of lithium and iron may be needed.

## BIOTITE.

Mono. (Pseudohexagonal) $(K,H)_2(Mg,Fe)_2(Al,Fe)_2(SiO_4)_3$

$$a : b : c :: 0.557 : 1 : 3.274$$

$$\beta = 90° 0'$$

Phys. Char. Crystals often much flattened prisms with hexagonal outline; more rarely triangular outline. Often in disseminated scales or lamellar aggregates. Twinning common on the mica law; often very thin lamellæ superposed in twinning position. This condition can be detected only by crystal faces, or by varying pleochroism || Z and Y in varieties with relatively large optic angle. Perfect basal cleavage yielding thin elastic laminae; also parting || 010, 1̄11, and several other pyramids, thus giving the pressure and percussion figures. H. = 2.5-3. G. = 2.7-3.2. Whitens and fuses on thin edges before the blowpipe. Decomposed by sulphuric acid leaving the silica in scales. Gives water and sometimes fluorine in the closed tube. Often bent, twisted, or even broken in rocks that have been under strain.

OPT. PROP. The plane of the optic axes is parallel to 010; the negative acute bisectrix is very nearly normal to 001. The angle of the optic axes is practically zero in most biotite of igneous rocks; an angle ($2E$) greater than 20° is quite rare, but this angle, especially in dark biotite, occasionally reaches 70°. The relief is distinct, and the birefringence very strong, being stronger in biotites rich in iron. Dispersion very weak $\rho < v$.

(—) $2E$ = usually near 0° (0°-15°)
= less commonly 15°-30°; rarely 30° to 70°.
$n_g = 1.638\text{-}1.574$ (varies directly with iron content).
$n_m = n_g$ nearly (varies directly with iron content).
$n_p = 1.586\text{-}1.541$ (varies directly with iron content).
$n_g - n_p = 0.033\text{-}0.060$ (varies directly with iron content).

Color black, green, brown, red, brownish yellow. Luster splendent more or less pearly on cleavage face, and vitreous on lateral faces. Streak colorless or gray. In thin section the absorption is often Z > Y > X, but sometimes it is Y > Z > X; usually the absorption || Z and || Y is practically equal. Pleochroism is very distinct, as follows:—

| Dark yellow | Brown | Dark brown | Green |
|---|---|---|---|
| Z=golden yellow | reddish brown | dark to opaque brown | grass green to black |
| Y=reddish brown | reddish brown | dark to opaque brown | grass green to black |
| X=colorless | pure yellow | pure yellow | pale to dark yellow |

INCL. Pleochroic halos are more abundant about inclusions in biotite than in any other mineral. These inclusions may be zircon, apatite or titanite; less commonly allanite, rutile, or fluid inclusions. The pleochroism in the halos is similar in color and position to the pleochroism of the biotite itself, but it is more intense, so that the halo is often opaque || Z and || Y. The refringence and the birefringence are greater in the halo than in other parts of the biotite. If the biotite be heated to a high temperature (but not fused) the halos disappear.

ALTER. Biotite alters readily to chlorite; this alteration may be direct or it may be indirect. In the latter case a brown biotite first changes color to green, and the laminæ become flexible and inelastic; still the birefringence remains very strong. Finally the green color becomes paler, the birefringence decreases, and chlorite results, often accompanied by epidote, calcite, quartz, etc. At the same time rutile, octahedrite, or brookite may be formed.

Biotite is sometimes altered by the loss of the alkalies and hydrogen to a brown or yellow mineral with bronze luster. This mineral has soft, flexible, inelastic laminæ; heated to 100° C. it loses water, at a higher temperature it exfoliates and opens out into worm-like forms (hence the name *vermiculite*). It possesses the strong birefringence and other optical characters of biotite and the micas. This strong birefringence distinguishes it sharply from the chlorites. The chemical composition of the mineral is not well known, but it seems to be quite variable, as if there were a group of vermiculites.

Biotite suffers noteworthy modifications under the metamorphosing action of heat (and pressure). Very often the exterior of the biotite changes without loss of form to magnetite, sometimes accompanied by augite; finally, biotite may recrystallise, at least in part. In other cases the biotite may be modified in part to hematite, or, by more heat, to magnetite, spinel and hypersthene, with, more rarely, sillimanite and recrystallisations of biotite.

OCCUR. Biotite is an important constituent of many igneous rocks, being found in eruptive rocks of all ages and nearly all classes. It is also found in various metamorphic rocks, such as gneiss and micaschist, where it may accompany or replace the muscovite. It is a product of both regional and contact metamorphism, but phlogopite is much more abundant in crystalline limestone, dolomite, etc., than biotite. Finally, biotite is found in unaltered sedimentary rocks (usually altered to chlorite) where it has been deposited from suspension.

**Roscoelite** is a vanadium mica of doubtful formula, perhaps $H_8K_2(Mg,Fe)(Al,V)_4(SiO_3)_{12}$. It is like biotite, but has $G. = 2.92$-$2.94$, and reacts for vanadium. Negative acute bisectrix normal to basal cleavage. Optic angle moderate; dispersion $\rho < v$. Color dark clove brown to dark brownish green. Pleochroism distinct. Found closely associated with gold ores, especially gold tellurides. Rare.

DIAG. Biotite differs from the alkaline micas in the position of the optic plane, the small optic angle, and the color and pleochroism. It has darker color than phlogopite.

## ANOMITE.

MONOCLINIC $(K,H)_2(Mg,Fe)_2(Al,Fe)_2(SiO_4)_3$

PHYS. CHAR. Very similar to biotite, of which it is usually considered a variety. But it differs optically, and Tschermak assigns to it a formula containing an excess of K over basic H, while he believes biotite to contain as much (or more) H as K. Twinning on the mica law very common.

OPT. PROP. The plane of the optic axes is normal to 010; the negative acute bisectrix is nearly normal to 001, but in general makes a greater angle with a normal to 001 than in biotite; this angle may reach 4° in anomite, and in such a case the twinning laminæ are easily distinguished in sections normal to 001. The angle of the optic axes is usually very small ($2E$ = about 10°), but it may reach much larger angles (25°, 40°, 68°). The dispersion is sometimes $\rho > v$, but more commonly $\rho < v$. The color of anomite is always brown or reddish, never green. The pleochroic colors are those of brown biotite. The absorption is sometimes $Z > Y$, sometimes $Y > Z$, but always $X < Y$ and $Z$.

OCCUR. Anomite is similar to biotite in its mode of occurrence, but is not so common.

**MICROCLINE,** see feldspar group. **MICROSOMMITE,** see nephelite group. **MIERSITE,** see marshite. **MILLERITE,** see cinnabar group. **MIMETITE,** see apatite group.

## MIRABILITE.

MONOCLINIC $a:b:c::1.116:1:1.237$ $Na_2SO_4 + 10H_2O$

$\beta = 72° 15'$

PHYS. CHAR. Crystals like pyroxene in habit and angles. Usually in efflorescent crusts. Twinning on 100 rare. Cleavage perfect || 100, in traces || 001 and 010. H. = 1.5-2. G. = 1.48. Soluble in $H_2O$; taste, cool, then bitter.

OPT. PROP. The optic plane and acute bisectrix X are normal to 010; the axis Z makes an angle of +31° with $c$ in red light and +26½° in blue light. Crossed dispersion strong. $2E = 122° 48'$ Li. Color white.

OCCUR. Abundant in some hot springs; formed in quantity from some salt lakes; also formed by the action of volcanic gases upon salt water.

DIAG. Distinguished by its mode of occurrence, its crystal form, its efflorescent character, and its taste. Optically, it is negative, with large extinction angle, large optic angle, and strong dispersion.

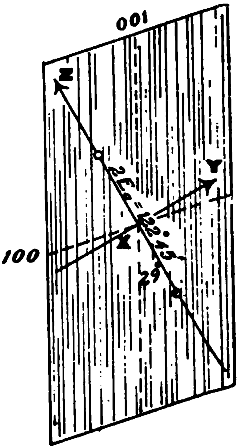

Figure 150.
Optical orientation of mirabilite.

## MOISSANITE

RHOMBOHEDRAL $c = 1.2264$ SiC

PHYS. CHAR. Crystals usually thin hexagonal basal plates often perfect on one side only; rhombohedral faces small. Twinning on $10\bar{1}1$ rare. Cleavage or parting poor || 0001; fracture conchoidal, distinct. H. = 9.5 +. G. = 3.05 - 3.23. Infusible, but dissociates at about 3400°C. Insoluble even in HF.

Opt. Prop. Uniaxial and positive. Jewell[1] reports the refringence very high, the birefringence extremely strong, and the dispersion remarkably great, as follows:—

| | Li | Na | Tl | $CuSO_4$ |
|---|---|---|---|---|
| $n_g$ = | 2.86 | 2.97 | 3.07 | 3.25 |
| $n_p$ = | 2.76 | 2.83 | 2.90 | 3.03 |
| $n_g - n_p$ = | 0.10 | 0.14 | 0.17 | 0.22 |

Measurements of the refractive index in sodium light by the method of Chaulnes verify Jewell's determination for the ordinary ray ($n_p$), but the interference figure from basal plates indicates a birefringence much nearer that of quartz than that of calcite. [A. N. W.]

Colorless when perfectly pure, but usually colored green, blue, red, black, by small amounts of iron, alumina, carbon, etc., present as impurities. Further, surface films of silica, often present, produce iridescent colors. Luster brilliant adamantine.

Occur. Found by Moissan in the Canon Diablo meteorite. It is an important artificial product of the electric furnace known commercially as carborundum.

## MOLYBDENITE.

Hexagonal $c = 1.908$ $MoS_2$

Phys. Char. Crystals tabular || 0001, or short prismatic; commonly foliated massive. Cleavage perfect || 0001; laminæ flexible inelastic. Feel greasy. H. = 1.-1.5. G. = 4.7-4.8. Infusible. Decomposed by $HNO_3$.

Opt. Prop. Opaque. Color lead gray. Streak slightly greenish (on glazed porcelain). Luster metallic.

Occur. Found embedded or disseminated in crystalline limestone, gneiss, vein quartz, granite, etc. Alters easily to molybdite.

## MOLYBDITE.

Orthorhombic $a : b : c :: 0.387 : 1 : 0.475$ $MoO_3$

Phys. Char. Crystals capillary, tufted, massive fibrous, earthy. Cleavage distinct || 001, in traces || 100 and 010. H. = 1.-2. G. = 4.49-4.5. Easily fusible. Soluble in HCl.

Opt. Prop. The optic plane is parallel to 100; the acute bisectrix Z is normal to 001. Birefringence strong; $n_g - n_g = 0.200$. Extinction parallel to positive elongation. Dispersion $\rho > v$ strong. $2H_o = 119°23'$ Na. Color pale to orange yellow. In thin section strongly pleochroic with Z dark orange yellow, Y = X pale yellow.

Occur. Found with molybdenite from which it is derived.

## MOLYBDOPHYLLITE.

Hexagonal $(Pb,Mg)_2SiO_4 + H_2O$

Phys. Char. Crystals unknown; in lamellar masses. Percussion figure distinct, like micas. Cleavage perfect || 0001. H. = 3.-4. G. = 4.72. Slowly fusible to a gray porcelain.

---

[1] Mineral Industry Vol. XVI. 1907. p. 153.

Opt. Prop. Uniaxial and negative. Color pale green. Colorless in thin section.

$$n_g = 1.8148 \text{ Na} \quad n_p = 1.7611 \text{ Na}$$
$$n_g - n_p = 0.0537$$

Occur. Found with hausmannite in limestone. Very rare.

## MONAZITE.

Monoclinic $a:b:c::0.969:1:0.926$ $(Ce,La,Di)PO_4$
$\beta = 76° 20'$

Phys. Char. Crystals usually small tablets || 100; sometimes elongated || $\bar{1}11$, or || *b*. In sands, rolled grains occur. In gneisses, microscopic crystals. In pegmatites sometimes larger crystals. Cleavage || 100 distinct; || 010 difficult. Parting || 001 sometimes perfect, sometimes distinct, sometimes absent. Twinning common on 100. H. = 5.5. G. = 4.9-5.3. Infusible. Difficultly soluble in HCl.

Opt. Prop. The plane of the optic axes is normal to 010; the positive acute bisectrix makes an angle of 2° to 6° with the vertical axis in the obtuse angle $\beta$. The relief is high and the birefringence is very strong. The angle of the optic axes is small. Dispersion weak $\rho < v$; also weak horizontal dispersion.

$$(+)\ 2E = 23° \text{ to } 31° \ (2V = 13° \text{ to } 15°)$$
$$n_g = 1.8411 \quad n_m = 1.7965 \quad n_p = 1.7957$$
$$n_g - n_p = 0.0454$$

Color yellowish to reddish brown, or red; pleochroism absent in thin section, but absorption is distinct from colorless to yellowish with Y > Z = X.

Occur. Occurs sparingly in microscopic crystals in some granite, gneiss, aplite, and pegmatite. Also in sands derived from these rocks. Thus in Brazil, North Carolina, etc.

Diag. Distinguished from olivine by the small optic angle; distinguished from titanite by much weaker birefringence, a smaller optic angle, a weaker dispersion, and the form.

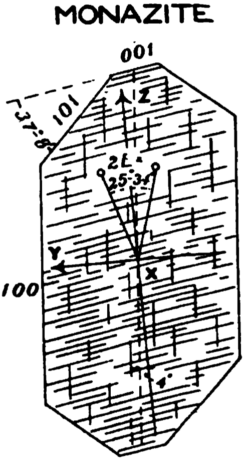

Figure 151.
Optical orientation of monazite.

**MONTICELLITE**, see olivine group. **MORDENITE**, see zeolite group. **MORENOSITE**, see epsomite group.

## MOSANDRITE and JOHNSTRUPITE.

Monoclinic $a:b:c::1.623:1:1.391$ $Ce_2Ca_8Na_3(F,OH)_7(SiO_3)_9$
$\beta = 86° 56'$

Phys. Char. Usually in long prismatic crystals, sometimes flattened || 100; vertical faces striated. Also in laminæ. Cleavage distinct || 100; in traces in thin sections || 010, and probably || 001. Twinning common on 100. H. = 4.-4.5. G. = 2.93-3.07 (mosandrite); 3.10-3.29 (johnstrupite). Gives water in the closed tube. Fuses with intumescence at 3. to a brown or gray glass. Readily soluble in HCl with separation of silica; the dark red solution gives off chlorine when heated. and turns yellow.

Opt. Prop. The plane of the optic axes is parallel to 010; the obtuse bisectrix makes an angle of about 2° with *c*. Twinning on 100 often polysynthetic. Refringence high; birefringence variable, as in epidote, with which these minerals are sometimes compared. Angle of the optic axes large about the positive bisectrix. Dispersion $\rho > v$ strong; also weak inclined dispersion.

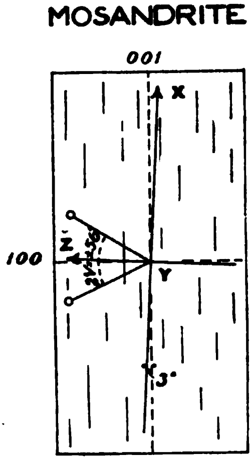

Figure 152.
Optical orientation of mosandrite.

| | Mosandrite. | Johnstrupite |
|---|---|---|
| (+) $2V =$ | 74° | 70° |
| $n_g =$ | 1.6577 | |
| $n_m =$ | 1.6490 | 1.546 (?1.646) |
| $n_p =$ | 1.6455 | |
| $n_g - n_p =$ | 0.0122 | |

Color brownish, green, reddish brown, yellowish; streak yellowish green or pale yellow. Colorless to pale yellow without pleochroism in thin section; in thick plates absorption Z > Y > X with Z = greenish yellow, Y = brownish yellow; X = bright yellow.

Incl. Often contain inclusions of fluorite, eucolite, etc.

Alter. Alter easily to dark brown to opaque unknown substance; calcite and ægirite may also form.

Occur. Found in pegmatite in eleolite syenite and related rocks in Norway. Rare.

Diag. Distinguished from rinkite by the position of the plane of the optic axes and the strong dispersion $\rho > v$; distinguished from hiortdahlite by the crystal system and the cleavage.

**MUSCOVITE,** see mica group.

## NARSARSUKITE.

Tetragonal $c = 0.524$ $Na_6FeFTi_2Si_{12}O_{32}$?

Phys. Char. Crystals tabular || 001 or short prismatic. Cleavage perfect || 110. H. = 7. G. = 2.75. Easily fusible. Soluble only in HF.

Opt. Prop.. Uniaxial and positive. Color honey yellow to reddish. In thin section colorless; in thick sections irregularly colored and pleochroic, Z reddish yellow, X colorless.

$$n_g = 1.5842 \quad n_p = 1.5532$$
$$n_g - n_p = 0.031$$

OCCUR. Found abundantly at Narsarsuk in southern Greenland.

## NATROCHALCITE.[1]

MONOCLINIC $a:b:c::1.423:1:1.214$ $Na_2Cu_4(OH)_2(SO_4)_3+2H_2O$
$\beta=61° 17'$

PHYS. CHAR. Crystals steep double pyramids, with modifications. Cleavage perfect || 001. H. = 4.5. G. = 2.33. Easily fusible to a black bead. Slowly soluble in water.

OPTIC. PROP. The optic plane is parallel to 010; the acute bisectrix Z makes an angle of —12° with $c$. $Z_r \wedge c > Z_{bl} \wedge c$. The refringence is high and the birefringence extremely strong. The optic angle is moderate; the inclined dispersion is weak, but $\rho < v$ strong (3°).

$$(+) \quad 2V=36° 50'$$

$$n_g=1.7143 \quad n_m=1.6555 \quad n_p=1.6491$$

$$n_g-n_p=0.0652$$

Color bright emerald green in mass.

OCCUR. Found with chalcanthite, atacamite, and brochantite in Chile. Very rare.

**NATROLITE,** see zeolite group. **NATROPHILITE,** see triphylite.

### Nephelite Group.

This group includes several silicates of aluminum with sodium, potassium, or lithium, as well as other elements in certain cases. The minerals are all hexagonal, usually in prisms either long or short, or in aggregates. They are chiefly orthosilicates, although nepheline itself does not seem to be a simple orthosilicate. The minerals of the group are as follows:—

| | | |
|---|---|---|
| Nephelite | $c=0.8389$ | $K_2Na_6Al_8Si_9O_{34}$ |
| Kaliophilite | | $KAlSiO_4$ |
| Eucryptite | | $LiAlSiO_4$ |
| Cancrinite | $2c=0.8819$ | $H_6Na_6Ca(NaCO_3)_2Al_8(SiO_4)_9$ |
| Microsommite | $2c=0.8367$ | $(Na_2,Ca,K_2)_{16}(Cl,NaSO_4,NaCO_3)_{11}Al_{25}Si_{24}O_{96}$ |

## NEPHELITE.

HEXAGONAL $c=0.8389$ $K_2Na_6Al_8Si_9O_{34}$

PHYS. CHAR. Crystals usually thick six or twelve-sided prisms with base prominent; also massive, and in embedded grains. Cleavage imperfect || 10$\bar{1}$0, better in partially altered samples; cleavage difficult || 0001. H. = 5.5-6. G. = 2.55-2.65. Fuses quietly at 3.5 to colorless glass. Soluble in acids with gelatinization.

OPT. PROP. Uniaxial and negative. Refringence low; birefringence very weak.

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[1] Palache and Warren: *Amer. Jour. Sc.* XXVI. 1908. p 345.

| | Penfield | Zambonini | Zimanyi |
|---|---|---|---|
| $n_g =$ | 1.5469 | 1.5428 | 1.5364 |
| $n_p =$ | 1.5422 | 1.5380 | 1.5322 |
| $n_g - n_p =$ | 0.0047 | 0.0048 | 0.0042 |

Colorless, or tinted by impurities. Luster vitreous to greasy. Colorless in thin section.

Alter. Nephelite alters in various ways; it may change to a mass of fibrous zeolites (natrolite, and hydronephelite, sometimes with thomsonite, or christianite), or to analcite, or sodalite; very frequently it changes to cancrinite, this change occurring first along the cleavage cracks and finest fracture lines, and finally replacing the whole mass. In this change the cancrinite often has a uniform orientation, which may be that of the original nepheline crystal. Further, nephelite often changes in a similar way to muscovite; in this case the laminæ of mica are commonly parallel to the basal cleavage of the nepheline in which they form. The mica formed is colorless, containing potassium and having a small optic angle. It has been called *liebenerite,* and also *gieseckite.* Calcite may form at the same time. Finally, more rarely, nephelite alters to kaolinite, to garnet, or to a colloidal substance of unknown nature.

Occur. Nephelite is found only in sodic igneous rocks, that is, in nephelite syenite, in phonolite, in nephelite basalt, and in theralite.

**Kaliophilite** (also called *phacelite*) is a potash nephelite, of uniaxial negative character, found in ejected masses from Mt. Somma, Italy. It is produced by the action of the lava on adjacent rocks, including limestone. **Eucryptite** is a lithium nephelite found as an alteration product of spodumene at Branchville, Conn.

Diag. Distinguished from apatite (also gehlenite and melilite) by much lower refringence giving no relief, from the sodalite group by the birefringence, from the scapolite group by weaker birefringence, and different cleavage, and from orthoclase by uniaxial character, absence of twinning, cleavage, and easy gelatinization with acids. The alteration products are also rather characteristic.

## CANCRINITE.

Hexagonal $2c = 0.8819$ $H_6Na_6Ca(NaCO_3)_2Al_8(SiO_4)_9$

Phys. Char. Usually massive; rarely in hexagonal prisms terminated by low pyramids. Cleavage perfect || $10\bar{1}0$, difficult parallel $11\bar{2}0$. H. = 5.-6. G. = 2.42-2.5. Gives water in the closed tube. Fuses at

2 with intumescence to a white blebby glass. Effervesces with acids; gelatinizes on heating in acids.

Opt. Prop. Uniaxial and negative. Refringence low; birefringence strong.

$$n_g = 1.5244 \quad n_p = 1.4955$$
$$n_g - n_p = 0.0289$$

Color white, or tinted by impurities. Colorless in thin section.

Alter. Rarely alters to natrolite.

Occur. Found apparently as a primary constituent of certain igneous rocks associated with nephelite; also a common alteration product from nephelite.

Diag. Distinguished from nephelite by much stronger birefringence (also by ready fusibility and effervescence); distinguished from the scapolite group by the differing cleavage, and from the calcite group by the cleavage and the much weaker birefringence; finally, distinguished from thomsonite by its uniaxial character.

## MICROSOMMITE.

Hexa. $2c = 0.8367$ $(Na_2.Ca.K_2)_{16}(Cl,NaSO_4.NaCO_3)_{11}Al_{25}Si_{24}O_{93}$

Phys. Char. Minute long prismatic crystals, vertically striated, terminated by the base. Cleavage perfect || $10\bar{1}0$, imperfect || 0001. H. = 6. G. = 2.42-2.53. Fuses with difficulty. Decomposed with gelatinization by HCl.

Opt. Prop. Uniaxial and positive. Refringence low; birefringence very weak. Colorless.

$$n_g = 1.529 \quad n_p = 1.521$$
$$n_g - n_p = 0.008$$

Occur. Very rare. Found in ejected masses and leucitic lavas from Mt. Somma, Italy. *Davyne* is a variety of microsommite, probably differing chemically in the $(Cl.NaSO_4.NaCO_3)$ present. It has very weak birefringence; $n_g = 1.5199$ to $1.5222$, $n_p = 1.5174$ to $1.5199$, $n_g - n_p = 0.0025$ to $0.0023$. *Cavolinite* seems to be a synonym of davyne. Both are found at Vesuvius.

Diag. Distinguished from nephelite by the optic sign; from quartz by weaker birefringence and cleavage. Other diagnostics similar to those of nephelite.

## NESQUEHONITE.

Orthorhombic $a : b : c :: 0.644 : 1 : 0.457$ $MgCO_3 + 3H_2O$

Phys. Char. Crystals long prismatic, vertically striated; often radiating. Cleavage perfect || 110, imperfect || 001. H. = 2.5. G. = 1.84.

Opt. Prop. The optic plane is parallel to 001; the acute bisectrix X is normal to 100. Dispersion $\rho < v$ weak. Colorless to white.

$$(-) \quad 2E = 84^\circ\,15'\,Na \quad (2V = 53^\circ\,5'\,Na)$$
$$n_g = 1.526 \quad n_m = 1.501 \quad n_p = 1.495$$
$$n_g - n_p = 0.031$$

Occur. Found in coal mines with lansfordite. Very rare.

## NEWBERYITE.

ORTHORHOMBIC $a:b:c::0.955:1:0.936$ $HMgPO_4 + 3H_2O$

PHYS. CHAR. Crystals equidimensional, elongated || *c*, or tabular || 100, much modified. Cleavage perfect || 010, imperfect || 001. H. = 3.-3.5. G. = 2.10. Soluble in $HNO_3$.

OPT. PROP. The optic plane is parallel to 010; the acute bisectrix Z is normal to 001. $2E = 69° 47'$ Li. $(2V = 44° 47'$ Na). $n_m =$ 1.5196. Color white.

OCCUR. Found in guano. Very rare.

## NITER.

ORTHORHOMBIC $a:b:c::0.591:1:0.701$ $KNO_3$

PHYS. CHAR. Crystals acicular; in silky tufts, crusts. Twinning on 110 as in aragonite. Cleavage perfect || 011, imperfect || 010 and 110. H. = 2. G. = 2.09-2.14. Deflagrates vividly on live coal; violet flame color. Soluble in $H_2O$. Taste saline and cooling.

OPT. PROP. The optic plane is parallel to 100; the acute bisectrix X is normal to 001. Refringence very low; birefringence extremely strong. Becomes rhombohedral and uniaxial at 300°C. Color white. Luster vitreous.

$$(-)\ 2E = 7\tfrac{1}{2}° \text{-} 10°$$

$$n_g = 1.506 \quad n_m = 1.505 \quad n_p = 1.334$$

$$n_g - n_p = 0.172$$

OCCUR. Forms crusts on the surface of the earth, on walls and floor of caves in limestones, etc. Usually produced in part from decaying animal refuse.

## NORTHRUPITE.

ISOMETRIC $MgCO_3 \cdot Na_2CO_3 \cdot NaCl$

PHYS. CHAR. Crystals octahedral. Cleavage absent. H. = 3.5-4. G. = 2.38. Fusible at 1 with frothing. Easily soluble.

OPT. PROP. Isotropic. Index $n = 1.5144$ Na. Colorless to pale yellow, gray, or brown.

OCCUR. Found in a clay bed below Borax Lake, California. Rare.

**NOSELITE,** see sodalite group.

## OCTAHEDRITE (Anatase).

TETRAGONAL $c = 1.777$ $TiO_2$

PHYS. CHAR. Commonly octahedral in aspect; also tabular or prismatic. Cleavage distinct || 001 and 111. H. = 5.5-6. G. = 3.82-3.95. Infusible. Insoluble. Gives tests for titanium.

OPT. PROP. Uniaxial and negative. Refringence extremely high. Birefringence very strong.

| | Schrauf | Miller | Wülfing |
|---|---|---|---|
| $n_g =$ | 2.534 | 2.554 | 2.5618 |
| $n_p =$ | 2.496 | 2.493 | 2.4886 |
| $n_g - n_p =$ | 0.038 | 0.061 | 0.0732 |

Color brown to black. Luster adamantine. Streak colorless. In thin section colorless, blue, or yellow, sometimes variable in a single crystal. Pleochroism usually imperceptible in thin sections. In thick sections Z = pale blue or yellow, X = dark blue or orange.

OCCUR. Found rarely in igneous rocks, sometimes as a decomposition product.

DIAG. Easily distinguished from rutile and brookite by its uniaxial negative character. The crystal form is also characteristic, being usually octahedral in aspect.

## OKENITE.

ORTHORHOMBIC Axial ratio unknown. $H_2Ca(SiO_3)_2 + H_2O$

PHYS. CHAR. Crystals acicular, usually interlacing; compact fibrous. Cleavage in the prismatic zone indistinct. H. = 4.5-5. G. = 2.28-2.36. Fusible. Gelatinizes with HCl.

OPT. PROP. The optic plane is parallel to *c*; the acute bisectrix X is normal to a face of the prismatic zone of elongation.

$$(-)\ 2V = \text{large}$$
$$n = 1.556$$
$$n_g - n_p = 0.009$$

Color white, yellowish or bluish; sometimes yellow by reflected light, and blue by transmitted. Colorless in section.

OCCUR. Found in cavities in basic igneous rocks associated with zeolites. Rare.

**OLIGOCLASE,** see feldspar group.

## OLIVENITE.

ORTHORHOMBIC $a:b:c::0.940:1:0.673$ $Cu(CuOH)AsO_4$

PHYS. CHAR. Crystals prismatic to acicular; also fibrous, lamellar, reniform, granular. Cleavage in traces || 110, 010, and 011. H. = 3. G. = 4.1-4.4. Fusible at 2; crystalline on cooling. Soluble in $HNO_3$.

OPT. PROP. The optic plane is parallel to 001; the positive acute bisectrix is normal to 100. Dispersion $\rho < v$ large. Refringence high, $n = 1.83$. $2H_a = 106° 6'$ Na. Color shades of olive green to blackish green, brown, yellow, white. Streak olive green to brown.

OCCUR. Found in veins of copper mines. Uncommon.

**Adamite** [$Zn(ZnOH)AsO_4$] is isomorphous with olivenite; $a:b:c::0.973:1:0.716$; crystals prismatic or elongated || *b*. Often in crusts. Cleavage distinct || 101. H. = 3.5. G. = 4.35. Fusible. Soluble in HCl. Optic plane parallel to 001; acute bisectrix Z normal to 010. Dispersion $\rho < v$ large. $2H_a = 100°-108°$ Li. Color yellow, violet, red, green, colorless. Streak white. Found with zinc ores. Rare.

**Libethenite** [$Cu(CuOH)PO_4$] is in the same isomorphous group; $a:b:c::0.960:1:0.702$; crystals short, prismatic, drusy; also reniform compact. Cleavage indistinct || 100 and 010. H. = 4. G. = 3.6-3.8. Fusible at 2 with green flame color. Soluble in $HNO_3$. Optic plane parallel to 001; acute bisectrix X normal to 010. Dispersion $\rho > v$ large. $2V = 81° \, 8'$ Na; $n_m = 1.743$. Color olive green, usually dark. Streak olive green. Luster resinous. Found in veins in copper mines. Rare.

**Descloizite** [$(Pb,Zn)(PbOH)VO_4$] also belongs in the same group; $a:b:c::0.955:1:0.805$. Crystals short prismatic or pyramidal, often drusy; also stalactitic or massive fibrous. Cleavage none. H. = 3.5. G. = 5.9-6.2. Fusible. Soluble in cold $HNO_3$. Optic plane parallel to 010; negative bisectrix normal to 001; sign ±; optic angle very large, $2H = 97°$; dispersion $\rho < v$ strong. Refringence high, $n = 1.83$. Birefringence strong. Color red, brown, black. Streak orange to brownish red or yellowish gray. Luster greasy. Found in veins associated with vanadinite, pyromorphite, etc. Rare.

### Olivine Group.

The olivine group includes several minerals which are all orthosilicates of bivalent metals, crystallizing in the orthorhombic system. They are commonly found in embedded grains or in short prismatic crystals terminated by pyramids and domes. They have high refringence and strong birefringence, with a large optic angle. They are readily attacked by acids with gelatinization; they alter very easily.

The minerals of the group include the following:—

| | | |
|---|---|---|
| Tephroite | $a:b:c::0.4621:1:0.5914$ | $Mn_2SiO_4$ |
| Glaucochroite | $a:b:c::0.440:1:0.566$ | $MnCaSiO_4$ |
| Monticellite | $a:b:c::0.4337:1:0.5757$ | $MgCaSiO_4$ |
| Forsterite | $a:b:c::0.4666:1:0.5868$ | $Mg_2SiO_4$ |
| Chrysolite (Olivine proper) | $a:b:c::0.4657:1:0.5865$ | $(Mg,Fe)_2SiO_4$ |
| Titanolivine | | $(Mg,Fe)_2(Si,Ti)O_4$ |
| Fayalite | $a:b:c::0.4584:1:0.5793$ | $Fe_2SiO_4$ |

In the forsterite-chrysolite-fayalite series the angle of the optic axes varies directly with the percentage of FeO. Thus, if the angle be measured constantly about X, $2V$ is about 94° in forsterite with very little FeO; it is about 91° in olivine that contains 10% FeO; it passes 90°, the sign becoming — at 12% FeO; in hortonolite with 47% FeO it is about 70°; in fayalite with 68% FeO it is about 50°. At the same time the indices of refraction and the birefringence increase regularly.

## TEPHROITE.

ORTHORHOMBIC $a:b:c::0.4621:1:0.5914$ $Mn_2SiO_4$

PHYS. CHAR. Crystals rare; usually in crystalline masses. Cleavage distinct || 001; indistinct || 100; in traces || 010. H. = 5.5-6.

G. = 3.95-4.12. Fuses at 3.5 to a black scoria. Gelatinizes in acids.

Opt. Prop. The plane of the optic axes is parallel to 001; the negative acute bisectrix is normal to 010. Refringence high; birefringence strong. Optic angle large; dispersion $\rho > v$.

$$(-)\ 2V = 76° \pm \quad (2E = 160° \pm)$$

$$n_m = 1.80$$

Color ash gray (whence the name), grayish red, reddish brown, rose red. In thin section pleochroism distinct, with absorption Y > Z > X, and Z greenish blue, Y reddish, X brownish red.

Incl. Franklinite, willemite, and rhodonite occur as inclusions at times.

Occur. Found in ore deposits of manganese, zinc, etc. at Franklin Furnace, N. J., and in manganese deposits and metamorphic rocks in Sweden. Rare.

Diag. (See chrysolite). Distinguished from other minerals of the olivine group by its pleochroism.

## GLAUCOCHROITE.

Orthorhombic $a:b:c::0.440:1:0.566$ $MnCaSiO_4$

Phys. Char. Crystals prismatic; also in grains. H. = 6. G. = 3.4. Fuses quietly at 3. Easily soluble in HCl.

Opt. Prop. The optic plane is parallel to 001; the acute bisectrix X is normal to 010. Dispersion $\rho > v$ marked. Color bluish green. Colorless in thin fragments.

$$(-)\ 2V = 60°\ 51'$$

$$n_g = 1.735 \quad n_m = 1.722 \quad n_p = 1.686$$

$$n_g - n_p = 0.049$$

Occur. Found at Franklin Furnace with garnet, axinite, etc. Very rare.

## MONTICELLITE.

Orthorhombic $a:b:c::0.4337:1:0.5757$ $MgCaSiO_4$

Phys. Char. Crystals similar to chrysolite; also grains and masses. Cleavage indistinct || 010. H. = 5.-5.5. G. = 3.12-3.27. Fusible at 6. Soluble in HCl; evaporation produces gelatinization.

Opt. Prop. The plane of the optic axes is parallel to 001; the negative acute bisectrix is normal to 010. Refringence high; birefringence rather strong. Dispersion $\rho > v$.

$$(-)\ 2V = 37°\ 31'$$

$$n_g = 1.6679 \quad n_m = 1.6616 \quad n_p = 1.6505$$

$$n_g - n_p = 0.0174$$

Colorless or grayish; in thin section colorless.

Alter. Alters to serpentine; also to a variety of augite (*fassaite*).

Occur. Very rare. Found only in limestone, due to contact metamorphism.

Diag. Distinguished from chrysolite (also fayalite and forsterite) by poor cleavage, small optic angle, lower refringence and much weaker birefringence; further, most chrysolite is positive.

## FORSTERITE.

ORTHORHOMBIC $a:b:c::0.4666:1:0.5868$ $Mg_2SiO_4$

PHYS. CHAR. Crystals similar to chrysolite; sometimes flat || 100; elongated || *c;* also grains and masses. Twins rare on 031. Cleavage distinct || 010, difficult || 001. H. = 6.-7. G. = 3.21-3.33. Infusible. Gelatinizes with acids.

OPT. PROP. The plane of the optic axes is parallel to 001; the positive acute bisectrix is normal to 100; refringence high, birefringence strong, but less than that of chrysolite. Dispersion $\rho < v$.

(+) $2V = 86° 10'$

$n_m = 1.659$

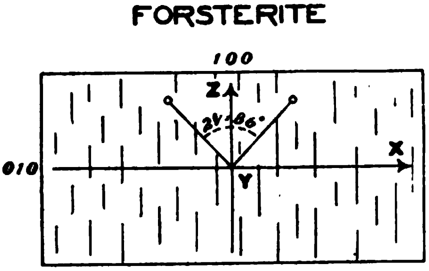

Figure 153. Optical orientation of forsterite.

Color white, yellowish, greenish; colorless in thin section.

INCL. Spinel sometimes is found abundantly as inclusions.

ALTER. May alter to a mineral resembling *villarsite* which is chemically a hydrated forsterite; this change seems to make no considerable change in the optic properties. Also alters to serpentine.

OCCUR. Forsterite is a mineral due to contact metamorphism of limestone or dolomite.

DIAG. (See chrysolite). Forsterite can be distinguished from chrysolite only by accurate measurement of the refringence, birefringence or optic angle, or by chemical analysis. However, the mode of occurrence may aid in differentiation.

## CHRYSOLITE (Olivine proper).

ORTHORHOMBIC $a:b:c::0.4657:1:0.5865$ $(Mg,Fe)_2SiO_4$

PHYS. CHAR. Crystals usually somewhat elongated || *c;* rarely elongated || *a;* commonly in imbedded grains or rounded crystals; also massive. Twinning rare on 011, and very rarely on 012. Cleavage distinct || 010, indistinct || 100. H. = 6.5.-7. G. = 3.2-3.34. Common olivine is infusible, but varieties rich in iron (*hyalosiderite,* with Mg : Fe :: 2 : 1, for example) fuse with difficulty to a black magnetic globule. Very easily attacked by acids (even acetic acid) with gelatinization.

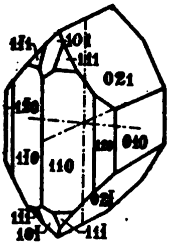

Figure 154. A crystal form of olivine.

OPT. PROP. The plane of the optic axes is parallel to 001; the bisectrix Z is normal to 100. Refringence high; birefringence strong. The angle of the optic axes is always very large. The dispersion is weak, and always $\rho < v$ about Z. Chrysolite is nearly always positive, but $2V$ about Z increases with the percentage of FeO; when that passes about 12 per cent. the angle passes 90° and the mineral becomes negative. At the same time the refringence increases. This may be shown in tabular form as follows:—

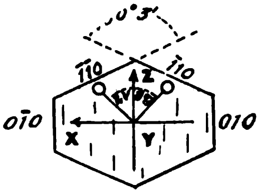

**Figure 155.** Optical orientation of olivine in basal section.

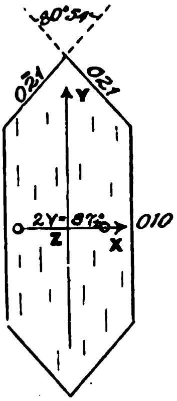

**Figure 156.** Optical orientation of olivine in macropinacoidal section.

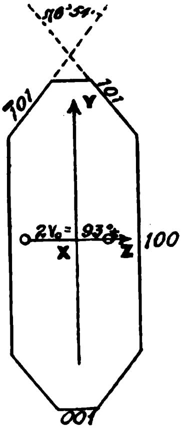

**Figure 157.** Optical orientation of olivine in brachypinacoidal section.

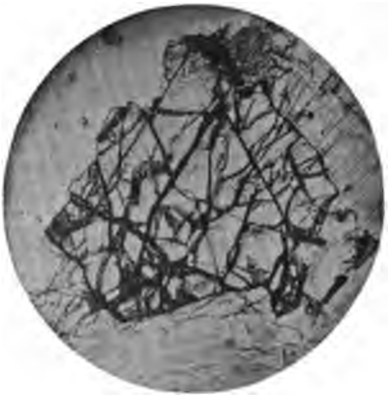

Figure 158. Section of olivine, showing high relief and alteration along fracture lines, in olivine gabbro from near Birch lake, Minn. W 1136. One nicol. × 45.

| Name | Locality | %FeO | $n_m$ | $2V$ about Z | Sign |
|---|---|---|---|---|---|
| Forsterite | Vesuvius | 2 approx. | 1.659 | 86° 10′ | + |
| Chrysolite | East Indies | 6 approx. | 1.670 | 87° 15′ | + |
| Chrysolite | Egypt | 9.2 | 1.678 | 88° 41′ | + |
| Chrysolite | Auvergne | 13.0 | 1.692 | 90° 24′ | — |
| Hyalosiderite | Norway | 24.0 | | 95° 10′ | — |
| Hortonolite | Monroe, Ct. | 47.3 | 1.791 | 110° 36′ | — |
| Fayalite | Rockport, Me. | 68.1 | 1.864 | 130° 10′ | — |

The indices of refraction and the birefringence are as follows:—

| | East Indies | Torre del Greco, Italy | Ural Mts. (with 10.7% FeO). |
|---|---|---|---|
| $n_g =$ | 1.6894 | 1.697 | 1.7089 |
| $n_m =$ | 1.6703 | 1.678 | 1.6899 |
| $n_p =$ | 1.6535 | 1.661 | 1.6720 |
| $n_g - n_p =$ | 0.0359 | 0.036 | 0.0369 |

Color olive green; by alteration yellow, brown or red. Luster vitreous. Streak colorless. Colorless to very pale greenish in section; by alteration of the iron becomes yellowish to red. Pleochroism wanting.

INCL. Inclusions are common of magnetite, spinel, apatite, and of vitreous, liquid or gaseous nature. Movable bubbles of liquid carbon dioxide are sometimes observed in cavities in olivine.

ALTER. Olivine alters very readily; indeed, it is much more commonly found altered than fresh. The alteration may give varying products, as follows:—The commonest alteration product of olivine is serpentine (either *antigorite* or *chrysotile*). In this case the olivine is changed to a hydrous magnesium silicate with, frequently, the separation of magnetite or hematite. Along the cleavage and fracture lines, which open markedly, the serpentine develops in fibers or laminæ, and finally the whole mass is transformed to serpentine. Quite often olivine alters to a mineral probably related to the serpentines, but containing considerable iron and showing distinct optical properties. This alteration may result in fibers or laminæ, or it may result in a compact mineral having the same orientation as the original crystal of olivine. The resultant mineral may be *bowlingite*, *xylotile*, or, (with nickel) *garnierite*. Antigorite and chrysotile in thin section are colorless or very pale green with weak birefringence; bowlingite and xylotile are yellow to brown and pleochroic with strong birefringence, while garnierite is bright green.

Another type of alteration quite common in olivine is the change to hematite, or limonite, or goethite. In this case the alteration takes place along cleavage and fracture lines, even when they are not opened, or it may attack the mineral with no reference to the cleavage lines on the borders or elsewhere.

Atmospheric weathering of olivine results in the formation of carbonates with limonite and opal (or quartz). The carbonates are often calcite, showing the removal of Mg and its replacement by Ca.

Regional metamorphism sometimes changes olivine to an amphibole. This occurs only when the olivine is in contact with feldspar, and thus the pale green to colorless amphibole needles form a zone between the olivine and feldspar. More rarely still other minerals may form from olivine, as pyroxene, talc, etc.

Occur. Olivine is a common constituent of various igneous rocks, in some of which it is an essential part. It is found especially in basic igneous rocks where it is commonly associated with augite, hypersthene, plagioclase feldspar, magnetite, etc. Further, it is not uncommon in crystalline limestone and dolomite; varieties poor in iron are usually found here. It is occasionally found in small amount in ore deposits. Finally, olivine is an essential constituent of many meteorites, where it constitutes (with enstatite, chromite, etc.) the stony portion of the mass.

Diag. Olivine is easily recognized. When in crystals the sections show acute-angled ends, a high refringence, a shagreen surface, no color, strong birefringence, and a large optic angle. Extinction in the chief zones occurs parallel to the elongation and to the cleavages. Distinguished from diopside by poorer and unequal cleavages to which the extinction is parallel. Difficult to distinguish from orthorhombic humite when the crystal form is lacking without a chemical test for flourine; however, the optic plane is normal to the best cleavage in olivine and parallel to the cleavage in humite.

## TITANOLIVINE.

Orthorhombic? $(Mg,Fe)_2(Si,Ti)O_4$

Phys. Char. In indistinct crystals, or, more commonly, in rounded grains. Twinning, often polysynthetic, with twinning plane near 014. Cleavage absent. H. = 6. G. = 3.25-3.27. Infusible, but turns black when heated. Soluble in acids, giving tests for titanium.

Opt. Prop. Optical orientation unknown on account of lack of crystals, but supposed to be similar to chrysolite. Refringence high; birefringence strong. Optic angle large; dispersion distinct with $\rho < v$.

$$(+)\ 2V = 62^\circ\ \ (2E = 119^\circ\ 30')$$
$$n_g = 1.702\quad n_m = 1.678\quad n_p = 1.669$$
$$n_g - n_p = 0.033$$

Color reddish brown to dark red. In thin section pleochroism intense, as given below, similar to that of the humites, with absorption $X > Y = Z$.

Z = Y = bright yellow
X = deep reddish yellow

In twins sections normal to the acute bisectrix have extinction symmetrical to the twinning plane; the optic normal (Y) makes an angle of about 20° on each side of the twinning plane. If one individual of the twin is cut normal to the obtuse bisectrix the other is cut oblique to the optic plane; in this case extinction occurs in the two parts at the same time, but they differ in birefringence and pleochroic colors.

**Alter.** Alters to serpentine, like chrysolite.

**Occur.** Found in talcose schist in Tyrol and in Switzerland. Rare.

**Diag.** In mass resembles almandite garnet, but gives test for titanium after prompt attack by acids. In thin sections distinguished from staurolite by different pleochroic formula, much stronger birefringence, polysynthetic twinning, and the absence of geometric forms. Distinguished from chondrodite and clinohumite, as follows:—In sections normal to the positive bisectrix of twinned crystals the optic normal makes symmetrical angles of 20° in titanolivine, while the optic plane makes symmetrical angles of about 30° in chondrodite and 7° to 12° in clinohumite, with the twinning plane.

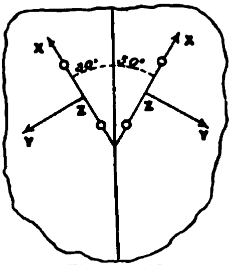

Figure 159. Optical orientation in a section normal to Z in a twin of chondrodite.

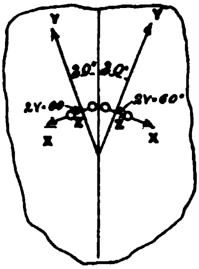

Figure 160. Optical orientation in a section normal to Z in a twin of titanolivine.

## FAYALITE.

**Orthorhombic** $a : b : c :: 0.4584 : 1 : 0.5793$ $Fe_2SiO_4$

**Phys. Char.** In minute crystals flattened ‖ 100; also in forms similar to chrysolite, and massive. Twinning rare on 011. Cleavage distinct ‖ 010, indistinct ‖ 100, in traces ‖ 001. H. = 6.-7. G. = 4.-4.14. Fuses readily to a black magnetic globule. Gelatinizes with acids.

**Opt. Prop.** The plane of the optic axes is parallel to 001; the negative acute bisectrix is normal to 010. Refringence high; birefringence very strong; optic angle large. Dispersion distinct with $\rho > v$.

$(-)\ 2V = 49^\circ\ 50'$

$n_g = 1.8736 \quad n_m = 1.8641 \quad n_p = 1.8236$

$n_g - n_p = 0.0500$

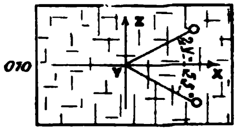

Figure 161. Optical orientation of fayalite in a basal section.

The optic angle becomes larger and the refringence and birefringence decrease as the iron is replaced by more and more magnesium (see chrysolite). Thus in the variety *hortonolite,* with about 18% of MgO, the optic angle ($2V$) is about 70°, and $n_g = 1.8031$, $n_m = 1.7915$, $n_p = 1.7684$, $n_g - n_p = 0.0347$.

Color pale greenish yellow; by oxidation of iron reddish brown to black. Usually colorless in thin section, but sometimes pale yellow with very weak pleochroism. In thin sections $Z = X =$ greenish yellow, and $Y =$ orange yellow. Absorption $Y > X > Z$. The pleochroism may at times be due to ferruginous inclusions.

ALTER. Similar to chrysolite, but iron products are more abundant.

OCCUR. Not abundant in nature; found in lithophyses in rhyolite in Yellowstone Park, etc.; also in other volcanic rocks, in pegmatite, and in some basic igneous rocks rich in iron of the Lake Superior region. Fayalite is the most abundant silicate found crystallized in many metallurgical slags. In these slags the mineral occurs with all the forms common in chrysolite; a vitreous residue is often abundant in fayalite thus formed.

**Knebelite** is intermediate in composition between fayalite and tephroite, that is, $(Fe,Mn)_2SiO_4$, but varieties are known with magnesium, thus grading toward hortonolite and hyalosiderite. Cleavage distinct || 110, indistinct || 100 and 001. G. = 3.9-4.17. Color gray, red, brown, yellow, green, black. Colorless to brown or green in thin section. Negative. Optical orientation as in fayalite. Optical angle large, $2G = 63^\circ\ 45'$. Dispersion $\rho > v$. The optic angle increases with decrease of the iron content. Found in iron manganese mines in Sweden. Very rare.

DIAG. (See chrysolite). Fayalite is distinguished from chrysolite by the higher refringence, stronger birefringence, and much smaller optic angle; further, chrysolite is usually positive. Fayalite is also more fusible.

## OPAL.

AMORPHOUS $SiO_2 + nH_2O$

PHYS. CHAR. Occurs in irregular grains, globules, masses, sometimes reniform, stalactitic, earthy, etc. It may be porous or earthy; it may be capable of absorbing much water, and thus becoming more transparent. Opal is usually much fractured. H. = 5.5-6.5. G. = 1.9-2.3. Variation in specific gravity is due to variation in the amount of water present (1 to 20%) and to the frequent existence of various impurities Infusible. Gives water in the closed tube. More soluble than quartz in HF.

Opt. Prop. Monorefringent, but rather frequently shows some polarization due to internal strain; globules then show a black cross of negative character like colloidal substances, e. g., gelatine, which contract on solidifying. Refringence varies apparently with the amount of water present.

$n = 1.44$-$1.45$ commonly.
$n = 1.406$ with very little water.
$n = 1.446$ after absorption of water.

Colorless, white, milky, yellow, brown, red, green, blue, black. Precious opal shows a play of colors. Colorless in thin section.

Incl. Inclusions of various pigments, etc., are common.

Alter. By loss of water opal changes to various forms of quartz such as normal quartz, quartzine, chalcedony, etc., or to tridymite.

Occur. Found in rocks of all kinds, but always of secondary origin. It may be formed by the alteration of silicates in igneous or metamorphic rocks; it may be deposited from solution about geysers or in veins, or cavities; it may be of organic origin; or it may be of concretionary origin in sedimentary rocks.

Diag. The distinctive characters of opal are the monorefringent character, the low refringence, the mode of formation, the colloidal structure, the low specific gravity, and the solubility in alkalies as well as in HF.

## ORPIMENT.

Orthorhombic $a:b:c::0.603:1:0.674$ $As_2S_3$

Phys. Char. Crystals small, indistinct; usually foliated massive. Cleavage perfect || 010, in traces || 100; gliding plane || 001. Laminæ flexible, inelastic. H. = 1.5-2. G. = 3.4-3.5. Wholly volatile before the blowpipe. Soluble in aqua regia.

Opt. Prop. The optic plane is parallel to 001; the positive acute bisectrix is normal to 100. Dispersion $\rho > v$, very strong.

$$(+)\ 2E = 70° 24'$$

Color lemon yellow. Streak pale yellow. Luster on cleavage pearly.

Occur. Found in hot springs and geyser deposits, in veins containing arsenic, in deposits from volcanic gases, and in clay. Also forms by sublimation in burning coal mines.

**ORTHOCLASE**, see feldspar group. **PACHNOLITE**, see cryolite. **PARAGONITE**, see mica group.

## PARISITE.

HEXAGONAL $c = 3.289$ $[(Ce,La,Di)F]_2Ca(CO_3)_3$

PHYS. CHAR. Crystals acute pyramidal, horizontally striated. Cleavage perfect || 0001. H. = 4.5. G. = 4.2-4.36. Infusible. Effervesces in HCl.

OPT. PROP. Uniaxial and positive. Refringence moderate; birefringence very high; $n_g = 1.670$; $n_p = 1.569$; $n_g - n_p = 0.101$. Color brownish yellow, streak yellow white. Colorless in thin section.

OCCUR. Found with beryl or eudidymite; also in quartz veins. Very rare.

**Synchysite** $[(CeF)Ca(CO_3)_2]$ is a related mineral very similar in form, but rhombohedral in symmetry. Cleavage none when unaltered. G. = 3.9. Infusible. Uniaxial and positive. $n_g = 1.7701$, $n_p = 1.6742$; $n_g - n_p = 0.0959$. Color light gray, wax gray, hair brown. In thin section straw yellow, gray, non-pleochroic, or feebly so. Sometimes shows a brown pigment in zones. Very rare.

## PECTOLITE.

MONOCLINIC $a : b : c :: 1.1140 : 1 : 0.9864$ $Na_2Ca(SiO_3)_2$
$\beta = 84° 40'$

COMP. Basic hydrogen is often present, and the formula is perhaps $HNaCa_2(SiO_3)_3$.

PHYS. CHAR. Crystals often flattened || 100 or elongated || *b*; commonly in close aggregation of acicular crystals or fibers. Twinning on 100. Cleavage perfect || 100 and 001. H. = 4.5-5. G. = 2.74-2.88. Fuses at 2. to white enamel. Partly decomposed by HCl with gelatinization. Yields water in closed tube.

OPT. PROP. The plane of the optic axes is normal to 010, to which the positive acute bisectrix is also perpendicular. The optic plane and obtuse bisectrix are nearly normal to 100. Refringence rather high; birefringence strong; optic angle large. The optic plane is nearly parallel to the elongation, which is positive.

$$(+)\ 2V = 60°.$$
$$n = 1.61.$$
$$n_g - n_p = 0.038$$

Colorless, whitish, gray; colorless in thin section.

OCCUR. Found in cavities or seams in basic igneous rocks; less commonly in metamorphic rocks.

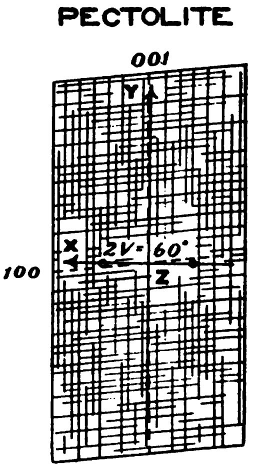

Figure 162.
Optical orientation of pectolite.

**Manganopectolite** with 4% MnO occurs in nepheline syenite of Magnet Cove, Ark.; it is of a clear green color, but is often clouded with brown oxide of manganese. Cleavage perfect || 001, less perfect || 100. Optic plane as in pectolite. Optic angle small, $2E = 15°$. Dispersion $\rho > v$, with very strong dispersion of the bisectrices, as in titanite.

DIAG. Distinguished from wollastonite by the position of the optic plane and Z with reference to the elongation, giving constant positive elongation.

**PENNINITE,** see chlorite group.

## PERCYLITE.

ISOMETRIC $PbCu(OH)_2Cl_2$?

COMP. AgCl is often present, and is perhaps an essential constituent.

PHYS. CHAR. Crystals minute cubes; also massive. H. = 2.5. G. = 5.25. Cleavage perfect || 100, imperfect || 111.

OPT. PROP. Isotropic or nearly so. Refringence very high. Color sky blue.

OCCUR. Found with lead or copper ores. Very rare.

**Boléite, pseudoboléite** and **cumengéite** are closely related to percylite and are thought by Lacroix to constitute a series with it in which the silver content continuously decreases to none in cumengéite. At the same time the specific gravity decreases to 5.08, 4.85, and 4.67. Further, the crystal form changes to tetragonal, and the length of the vertical axis decreases from 3.996 in boléite to 2.023 in pseudoboléite, and 1.625 in cumengéite. The mean index of refraction is near 2. in all the species, but the birefringence varies widely, from zero in percylite to 0.020 in boléite, 0.032 in pseudoboléite, and 0.100 ± in cumengéite. The anisotropic species are pseudoisometric and tetragonal; they are uniaxial and negative. But the latest analyses indicate variations in composition in these minerals not only in silver content, but also in the percentage of lead and water present. Found with copper ores. Very rare.

## PERICLASE.

ISOMETRIC MgO

PHYS. CHAR. In cubes, octahedrons, or grains. Perfect cubic cleavage; indistinct octahedral cleavage. H. = 5.5-6. G. = 3.64-3.67. Infusible. Soluble without effervescence.

OPT. PROP. Strictly isotropic. Cubic cleavage usually distinct in fine straight lines. Relief high.

$$n = 1.736.$$

Colorless to grayish or yellowish; brownish yellow, dark green; usually colorless in thin section.

ALTER. Alters readily to hydromagnesite, to serpentine, or to brucite.

OCCUR. Rare. Found in limestone modified by igneous action on Mte. Somma, in a manganese mine in Sweden, etc. Associated with monticellite, forsterite, spinel, magnesite, etc.

DIAG. Isotropic character, high relief, perfect cubic cleavage, and mineral associations are usually sufficient to identify the mineral.

## PEROVSKITE.

Pseudo-isometric $CaTiO_3$

Phys. Char. Crystals often cubic in aspect; also octahedral, trisoctahedral, etc. Also in rounded grains, or reniform masses. Intimate penetration twinning usually present. Cubic cleavage distinct in large crystals; not visible in thin section. H. = 5.5. G. = 4.02-4.04. Infusible. Decomposed by sulphuric acid.

Opt. Prop. Apparently isotropic in small crystals. In large crystals always anisotropic, with complex interlaced twinning, which may be explained like the twinning of garnet (pyrenéite) or boracite. The mineral is orthorhombic, or of lower symmetry at ordinary temperatures; it is probable that it is strictly isometric at the temperature and pressure of formation. Twinning often absent in small crystals. All the optic properties of the twins not fully known. Dispersion $\rho > v$ about Z.

$$(\pm)\ 2V = \text{about } 90^\circ$$

$$n = 2.38$$

$$n_g - n_p = 0.007 \text{ as a maximum; variable.}$$

Color pale yellow, orange yellow, reddish, brown, black; in transmitted light grayish, violet gray, brownish to reddish, rarely greenish. Colors sometimes arranged zonally.

Occur. Perovskite occurs well crystallized, especially in metamorphic rocks, both regional and contact. Also common as a microscopic element in melilite basalt and nepheline basalt. Here it is one of the first minerals to crystallize; therefore inclusions are rare; it may be formed by the alteration of ilmenite.

Diag. The extremely high refringence, the complex twinning, the color and the weak birefringence usually identify perovskite.

## PETALITE.

Monoclinic $a:b:c::1.1534:1:0.7436$ $LiAl(Si_2O_5)_2$

$$\beta = 67^\circ\ 34'$$

Phys. Char. Crystals rare, often elongated || $a$; usually in foliated cleavable masses. Cleavage perfect || 001, easy || 201, difficult || $\bar{9}05$. Colorless, or slightly tinted. H. = 6.-6.5. G. = 2.39-2.46. Phosphorescent on heating. Fusible at about 5. Soluble in HF (spodumene is insoluble). Insoluble in ordinary acids.

Opt. Prop. The plane of the optic axes is normal to 010; the positive acute bisectrix is normal to 010; the obtuse bisectrix makes an angle of 2° to 3° with 001 in the acute angle $\beta$; optic angle large. Dispersion $\rho < v$ weak; also weak crossed dispersion.

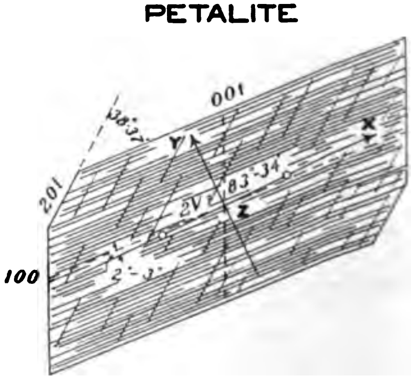

Figure 163. Optical orientation of petalite.

$$(+)\ 2V = 83^\circ\ 34'$$

$$n_g = 1.516\ n_m = 1.510\ n_p = 1.504$$

$$n_g - n_p = 0.012$$

Colorless or somewhat tinted. Colorless in thin section.

OCCUR. Rare. Found in pegmatites and similar rocks, and in some ore deposits. Often associated with spodumene, tourmaline, etc.

DIAG. Cleavage angle 141° between two unequal cleavages; large optic angle, positive character, low relief, rather weak birefringence, extinction nearly parallel to the best cleavage, which has negative direction.

## PHARMACOLITE.

MONOCLINIC $a:b:c::0.614:1:0.362$ $HCaAsO_4 + 2H_2O$

$$\beta = 83^\circ\ 13'$$

PHYS. CHAR. Crystals elongated || *a;* with domes; often fibrous to acicular; stalactitic; massive. Cleavage perfect || 010. H. = 2.-2.5. G. = 2.64-2.73. Fusible with intumescence and blue flame. Soluble in acids.

OPT. PROP. The optic plane and obtuse bisectrix Z are normal to 010; X makes an angle of +70° with *c*.

$$(-)\ 2H_o = 112^\circ\ 20'$$

$$n_g = 1.5937\quad n_m = 1.5891\quad n_p = 1.5825$$

$$n_g - n_p = 0.0112$$

Color white to grayish or reddish. Streak white.

OCCUR. Found with ores of cobalt and silver, and with arsenopyrite.

**Brushite** ($HCaPO_4 + 2H_2O$) is monoclinic with $a:b:c::0.622:1:0.342$ and $\beta = 84^\circ\ 45'$. Crystals slender, prismatic; also concretionary. Cleavage perfect || 010, and 301. H. = 2.-2.5. G. = 2.2-2.3. Fusible with intumescence. Soluble in dilute acids. Optic plane and acute bisectrix Z normal to 010; $X \wedge c = 10^\circ$. $2V = 85^\circ\ 43'$; $n_g = 1.5509$, $n_m = 1.5545$; $n_p = 1.5392$; $n_g - n_p = 0.0117$. Colorless to pale yellow. Streak white. Found in guano. Very rare.

**Haidingerite** ($HCaAsO_4 + H_2O$) is orthorhombic with $a:b:c::0.839:1:0.499$. Like pharmacolite in characters, but G. = 2.85. Optic plane parallel to 100; acute bisectrix Z normal to 001. Axial angle large. $n_g = 1.67$. Color white. Found with pharmacolite.

**Wapplerite** ($HCaAsO_4 + 3\frac{1}{2}H_2O$) is monoclinic (or triclinic?) with $a:b:c::0.913:1:0.266$ and $\beta = 84^\circ\ 35'$. Crystals small, highly modified; also globular, encrusting, reniform. Cleavage || 010. H. = 2.-2.5. G. = 2.48. Optic plane and acute bisectrix normal (or nearly normal) to 010; obtuse bisectrix makes an angle of —69° with *c*. $2E = 55^\circ$. Crossed dispersion with $\rho < v$. Colorless to white. Found with pharmacolite.

## PHARMACOSIDERITE.

ISOMETRIC $3FeAsO_4 \cdot Fe(OH)_3 + 6H_2O$?

COMP. Exact composition somewhat uncertain.

PHYS. CHAR. Crystals cubic, tetrahedral, or combined. Rarely granular. Cleavage imperfect || 100. H. = 2.5. G. = 2.9-3. Easily fusible. Soluble in HCl.

OPT. PROP. Isotropic; sometimes birefringent. Refringence high. $n = 1.676$. Color olive green to yellowish brown, yellow, green. Streak paler.

OCCUR. Found especially in copper mines with scorodite, enargite, etc.

## PHENACITE.

RHOMBOHEDRAL $c = 0.661$ $Be_2SiO_4$

PHYS. CHAR. Commonly in lenticular rhombohedral crystals, or in prisms more or less elongated || *c*. Twinning, commonly by penetration, with $10\bar{1}0$ as twinning plane. Cleavage difficult || $11\bar{2}0$ and $10\bar{1}1$. Fracture conchoidal or uneven. H. = 7.-8. G. = 2.96-3.00. Infusible. Insoluble.

OPT. PROP. Uniaxial and positive. Relief distinct.

$$n_g = 1.6697 \quad n_p = 1.6540$$
$$n_g - n_p = 0.0157$$

Colorless; also yellow, brown or red by infiltration of iron compounds. Usually colorless in thin section; the yellow variety in thick sections shows distinct pleochroism with Z yellow, X colorless.

OCCUR. Found in pegmatites and some metamorphic rocks. Rare.

**Willemite** ($Zn_2SiO_4$) is isomorphous with phenacite, with $c = 0.677$, and is like it in characters, but has cleavage || $11\bar{2}0$, or 0001. H. = 5.5. G. = 3.9-4.2. It is difficultly fusible and gelatinizes with HCl. Uniaxial and positive; $n_g = 1.7118$. $n_p = 1.6931$; $n_g - n_p = 0.0187$. Colorless white, greenish, yellow, apple green, flesh red, grayish white, yellowish brown. Streak colorless. Colorless in thin section. A variety containing considerable manganese is known as *troostite*. Found in zinc mines with franklinite, zincite, smithsonite, calcite; also with mimetite and wulfenite.

**Trimerite** [$(Be,Mn,Ca)_2SiO_4$] is related to phenacite in composition, but is pseudohexagonal ($c = 0.723$) and triclinic with $a : b : c :: 0.577 : 1 : 0.542$, and $\alpha = \beta = \gamma = 90 \pm$. Crystals thick tabular prismatic. hexagonal. Cleavage distinct || 001 (or 0001). H. = 6.-7. G. = 3.47. Fusible with difficulty. Soluble in HCl. Acute bisectrix nearly normal to 001; optic plane makes an angle of about 20° with 110. (—) $2V = 83° 29'$; $n_g = 1.7253$. $n_m = 1.7202$. $n_p = 1.7148$; $n_g - n_p = 0.0105$. Color pink, luster vitreous. Colorless in thin section. Found in calcite in a manganese mine. Very rare.

DIAG. The higher relief and slightly stronger birefringence distinguish phenacite from quartz. The crystal form and twinning (and hardness) also serve to differentiate it.

**PHILLIPSITE,** see zeolite group. **PHLOGOPITE,** see mica group.

## PHOSGENITE.

TETRAGONAL $c = 1.0876$ $(PbCl)_2CO_3$

PHYS. CHAR. Crystals prismatic, pyramidal to tabular. Cleavage distinct || 110 and 100, less distinct || 001. H. = 2.5-3. G. = 6.-6.3. Easily fusible. Effervesces in dilute $HNO_3$.

OPT. PROP. Uniaxial and positive. Refractive indices in orange light. $n_g = 2.140$, $n_p = 2.114$; $n_g - n_p = 0.026$. Color white, gray, yellow. Luster adamantine. Colorless in thin section.

OCCUR. Found in lead mines; formed by sea water acting on ancient lead slags in Greece. Alters to cerussite. Rare.

## PHOSPHOSIDERITE.

ORTHORHOMBIC $a:b:c::0.533:1:0.877$ $FePO_4 + 3\frac{1}{2}H_2O$

PHYS. CHAR. Crystals prismatic, rough. Cleavage perfect || 010. H. = 3.5-4. G. = 2.76. Easily fusible to magnetic bead. Soluble in HCl.

OPT. PROP. The optic plane is parallel to 010; the acute bisectrix Z is normal to 001. Optic angle large; dispersion $\rho > v$ strong.

$$(+)\ 2E = 126^\circ\ 26' \ (2V = 62^\circ\ 4')$$

$$n_m = 1.7315$$

Color red to violet. In section Z colorless, Y carmine, X pale pink.

OCCUR. Found in cavities in iron ore. Very rare.

## PICROMERITE.

MONOCLINIC $a:b:c::0.727:1:0.490$ $K_2Mg(SO_4)_2 + 6H_2O$

$\beta = 75^\circ\ 12'$

PHYS. CHAR. Crystals rare; usually in crusts. G. = 2.1-2.2. Yields water at low temperature.

OPT. PROP. The optic plane is parallel to 010; the acute bisectrix Z makes an angle of $-76^\circ$ with $c$. Dispersion $\rho > v$. $2E = 74^\circ\ 2'$. ($2V = 48^\circ\ 21'$). $n_m = 1.470$. Color white.

OCCUR. Found as a product of action of volcanic gases; also in some salt mines with kainite. Very rare.

**Cyanochroite** [$K_2Cu(SO_4)_2 + 6H_2O$] is isomorphous with picromerite, with $a:b:c::0.748:1:0.505$ and $\beta = 75^\circ\ 30'$. Usually in crusts. Optically like picromerite, but $Z \wedge c = -71^\circ$. $2E = 76^\circ\ 53'$. ($2V = 48^\circ\ 53'$). $n_m = 1.491$. Color blue. Found with picromerite on lavas. Very rare.

**Boussingaultite** [$(NH_4)_2Mg(SO_4)_2 + 6H_2O$] is isomorphous with picromerite, with $a:b:c::0.744:1:0.486$ and $\beta = 71^\circ\ 50'$. Crystals prismatic. G. = 1.68-1.72. Optic plane parallel to 010; acute bisectrix nearly parallel to $a$. $2E = 77^\circ\ 28'$. $n_m = 1.4737$. Found in waters containing borates, and about fumaroles. Very rare.

**PIEDMONTITE,** see epidote group. **PIRSSONITE,** see gaylussite. **PISANITE,** see melanterite. **PLAGIOCLASE,** see feldspar group. **PLATTNERITE,** see rutile group. **POLIANITE,** see rutile group. **POLLUCITE,** see leucite.

## POLYBASITE.

ORTHORHOMBIC $a:b:c::0.579:1:0.913$ $Ag_9SbS_6$

COMP. Copper commonly replaces some silver; arsenic often present.

PHYS. CHAR. Crystals six-sided tabular prisms. Twinning on 110 common. Cleavage imperfect || 001. H. = 2.-3. G. = 6.0-6.2. Fusible with spurting to globule. Decomposed by $HNO_3$.

OPT. PROP. The optic plane is parallel to 100; the acute bisectrix X is normal to 001. Optic angle variable, $2E = 62° - 88°$. Color iron black. Streak black. In thin section cherry red.

OCCUR. Found in veins with silver and copper ores.

## PREHNITE.

ORTHORHOMBIC $a:b:c::0.840:1:0.555$ $H_2Ca_2Al_2(SiO_4)_3$

PHYS. CHAR. Crystals rare; tabular || 001, prismatic or pyramidal. Often in aggregates of tabular crystals, fan-shaped or sheaf-like. Also globular, reniform, spherulitic. Cleavage distinct || 001, very difficult || 110. H. = 6.-6.5. G. = 2.80-2.95. Fuses at 2 with intumescence to a blebby enamel. Slowly soluble in HCl without gelatinization.

OPT. PROP. The plane of the optic axes is parallel to 010; the positive acute bisectrix is normal to 001. The relief is distinct, and high as compared with other minerals originating by alteration. The birefringence is strong. The angle of the optic axes is large and somewhat variable. The axial dispersion is weak and variable, usually $\rho > v$.

$$(+)\ 2V = 66° - 69° \quad (2E = 123° \pm)$$

$$n_g = 1.649 \quad n_m = 1.626 \quad n_p = 1.616$$

$$n_g - n_p = 0.033$$

Color pale green, apple green, gray, white. Colorless in thin section.

Optic anomalies are not uncommon in prehnite. Some sections show fine twinning lamellæ like those of microcline; sections parallel to 001 may show areas with twinning lamellæ parallel and normal to 100, having parallel extinction, the optic plane at right angles in the two sets of lamellæ, the optic angle very small and the interference figure exhibiting strong crossed dispersion; other areas may show incomplete extinction and abnormal interference colors. These facts suggest that the orthorhombic form may be due to microscopic twinning of monclinic individuals.

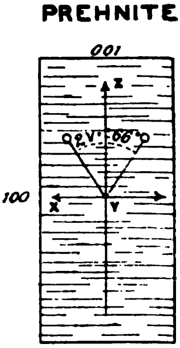

Figure 164. Optical orientation of prehnite.

INCL. Prehnite owes its green color largely to abundant inclusions, irregularly distributed, of chlorite. Similarly, limonite may give it a yellowish tint. Finally, asbestos occurs enclosed in it.

ALTER. The chlorite mentioned above may at times be an alteration product.

OCCUR. Prehnite is found chiefly in cavities in basaltic rocks associated with zeolites, datolite, pectolite, calcite. It is also found in cavities in crystalline schists, in crystalline limestone, and dolomite, and in metalliferous veins. It is a constituent of some amphiboles and related rocks.

Diag. Prehnite is distinguished from other colorless alteration products by its high refringence and strong birefringence; in these respects it most closely resembles thomsonite, but the latter is nearly always fibrous with elongation of variable sign. Prehnite is distinguished from andalusite, topaz and wollastonite by stronger birefringence, and from datolite by weaker birefringence and opposite sign.

**PROLECTITE**, see humite group. **PROSOPITE**, see cryolite. **PROUSTITE**, see pyrargyrite.

## PSEUDOBROOKITE.

Orthorhombic $a:b:c::0.9812:1:1.1268$ $Fe_4(TiO_4)_3$?

Phys. Char. Crystals small rectangular tablets flattened parallel to 100, usually striated parallel to the vertical axis. Cleavage distinct || 010. $H. = 6$. $G. = 4.4\text{-}4.9$. Nearly infusible. Decomposed by $H_2SO_4$.

Opt. Prop. The plane of the optic axes is parallel to 001. The positive acute bisectrix is normal to 100. Refringence high. Birefringence strong. Optic angle large. Distinct dispersion, with $\rho < v$.

$$(+)\ 2H_a = 84° 30'$$

Color dark brown to black, nearly opaque. Luster adamantine to greasy. In very thin sections reddish brown; pleochroism weak, with maximum absorption parallel to Y.

Occur. Found rarely in volcanic rocks and still more rarely in granitic rocks.

Diag. Resembles brookite in exterior characters, but may be distinguished by the form, the solubility in sulphuric acid, the larger optic angle and the absence of marked dispersion.

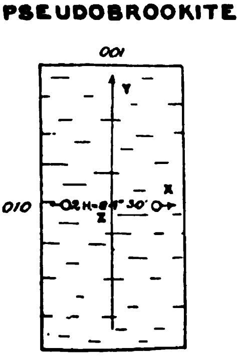

Figure 165.
Optical orientation of pseudobrookite.

## PSEUDOMALACHITE.

Triclinic? $a:b:c::2.825:1:1.534$ $(CuOH)_3PO_4$ in part

$\alpha = 89° 30'$ $\beta = 91° 1'$ $\gamma = 90° 40'$

Comp. The formula is doubtful because material is commonly massive and impure. Three species are sometimes distinguished:—*pseudomalachite*, $(CuOH)_3PO_4$, *ehlite* $Cu(CuOH)_4(PO_4)_2 + H_2O$, and *dihydrite* $Cu(CuOH)_4(PO_4)_2$. The axial ratio given above belongs to dihydrite, which alone has distinct crystals.

Phys. Char. Usually massive, reniform, botryoidal, with fibrous or lamellar texture. Cleavage imperfect || 010. $H. = 4.5\text{-}5$. $G. = 3.4\text{-}4.4$. Fusible at 2 giving green flame color. Soluble in $HNO_3$.

Opt. Prop. In dihydrite the acute bisectrix X is nearly normal to 101 and makes an angle of 68° with a normal to 100; the obtuse bisectrix makes an angle of about 5° with a normal to 010. Birefringence strong. $2E = 95°$. Color emerald green, blackish green. Streak paler. Luster vitreous. In thin section distinctly pleochroic with Z deep bluish green, Y yellowish green, X bluish green.

OCCUR. Found in copper veins in slate. Rare.

### PYRARGYRITE.

RHOMBOHEDRAL $c = 0.789$ $Ag_3SbS_3$

PHYS. CHAR. Crystals commonly prismatic and hemimorphic; twinning on $11\bar{2}0$ common with 0001 as composition face; twinning common on $10\bar{1}4$ either as simple or multiple twins; twinning on $10\bar{1}1$ uncommon. Massive, compact. Cleavage distinct || $10\bar{1}1$, indistinct || $01\bar{1}2$. H. = 2.5. G. = 5.77-5.86. Fusible with spurting. Decomposed by $HNO_3$, but only partly soluble.

OPT. PROP. Uniaxial and negative. Refringence extremely high, birefringence extremely strong.

$$n_g = 3.084 \quad n_p = 2.881$$
$$n_g - n_p = 0.203$$

Color black to grayish black. Streak purplish red. Luster metallic adamantine. In thin section red.

OCCUR. Found in veins with other silver ores and with galena, sphalerite, tetrahedrite, etc.

**Proustite** ($Ag_3AsS_3$) is isomorphous with pyrargyrite, with $c = 0.804$. Crystals often acute rhombohedral. Cleavage distinct || $10\bar{1}1$. H = 2.-2.5. G. = 5.57-5.64. Easily fusible. Decomposed by $HNO_3$. Uniaxial and negative; $n_g = 3.0877$, $n_p = 2.7923$, $n_g - n_p = 0.2953$. Color scarlet to aurora red. Luster adamantine. In thin section bright red. Occurs with pyrargyrite.

**Pyrostilpnite** ($Ag_3SbS_3$) has the composition of pyrargyrite, but is monoclinic with $a:b:c::1.947:1:1.097$ and $\beta = 90° \pm$. Crystals long prismatic often in tufts. Cleavage perfect || 010. H. = 2. G. = 4.25. Extinction angle on 010 8° to 11° from $c$. Color hyacinth red. Found with pyrargyrite. Very rare.

**Xanthoconite** ($Ag_3AsS_3$) has the composition of proustite, but a form like the preceding with $a:b:c::1.919:1:1.015$ and $\beta = 91° 13'$. Crystals pyramidal. Cleavage distinct || 001. H. = 2.-3. G. = 5.54. Optic plane normal to 010; acute bisectrix X nearly normal to 001. $2E = 125° \pm$. Dispersion $\rho < v$. Color orange to reddish brown. Streak orange yellow. Lemon yellow in section. Found with silver ores. Very rare.

## PYRITE.

ISOMETRIC. $FeS_2$

PHYS. CHAR. Crystals commonly cubes, pyritohedrons or octahedrons; faces often striated parallel to the edge $100 \wedge 210$. Also massive, fine granular, radiated, etc. Twinning usually by penetration with *a* as the twinning axis. Cleavage indistinct || 100 and 111. Opaque. H = 6.-6.5. G. = 4.95-5.1. In the closed tube gives a sulphur sublimate and a magnetic residue. Burns with a blue flame. Insoluble in HCl; decomposed by $HNO_3$.

OPT. PROP. Opaque. In reflected light pale brass yellow color and brilliant metallic luster. Streak greenish black. Polishes with difficulty and in relief on account of the hardness.

ALTER. Pyrite alters in nature quite readily; the process may be one chiefly of oxidation, or it may be largely hydration. In the first case the product is hematite, or, more commonly, limonite or göthite. In the second case the product is chiefly melanterite, sometimes mixed with copiapite, gypsum, halotrichite, etc. The alteration of pyrite usually results not only in the formation of new iron minerals, but also in the production of free sulphuric acid; therefore, altered pyrite is often accompanied by various other sulphates formed by the action of this free acid on surrounding minerals. Gypsum is very commonly produced in this way; in other cases the product may be alunogen, halotrichite, or still other sulphates.

OCCUR. Pyrite occurs under many varying conditions; it is one of the most widely distributed of minerals. Thus, it is found in many igneous rocks, usually in very small amount; it occurs in various metamorphic rocks likewise in small amount: it is found in some purely sedimentary rocks, in some cases being evidently of contemporaneous origin, but more frequently being deposited in the rock at a later date; finally, it is found often in abundance in many ore deposits, and hot spring deposits.

**Smaltite** ($CoAs_2$) and **chloanthite** ($NiAs_2$) are isomorphous with pyrite. Cleavage distinct parallel 111, in traces || 100. H. = 5.5-6. G. = 6.4-6.6. Fusible to a globule. Opaque. Color tin white to steel gray. Streak grayish black. Luster metallic. Alters to erythrite. Found in veins and ore deposits.

**Cobaltite** (CoAsS) belongs to the same group. Crystal cubes, pyritohedrons, or modified. Massive. Cleavage distinct || 100. H. = 5.5. G. = 6.-6.3. Fusible to magnetic globule. Soluble in $HNO_3$. Opaque. Color silver white to dark grayish, always tinged with red or violet.

Streak grayish black. Luster metallic. Found in ore deposits. Uncommon.

Diag. Pyrite is distinguished from many opaque minerals by the pale brass yellow color and metallic luster; distinguished from chalcopyrite by paler color and greater hardness, giving poorer polish. Pyrrhotite has a pale bronze yellow color, is softer than pyrite, and is readily attacked by HCl, which pyrite resists. Difficult to distinguish from marcasite in the absence of crystal form, but marcasite has a slightly paler color, a lower density, and alters more readily.

### Pyrochlore Group.

Isometric Niobates and tantalates.

Comp. The composition of these minerals is too complex and imperfectly known to permit writing definite formulas. *Pyrochlore* is chiefly a niobate of the cerium metals, calcium, etc., with titanium, thorium, and fluorine; ***koppite*** is essentially a pyroniobate of cerium, calcium, etc.; ***hatchettolite*** is a hydrous tantalo-niobate of uranium, calcium, etc.: *pyrrhite* (also called microlite) is essentially a pyrotantalate of calcium with some niobium; ***dysanalite*** is a titano-niobate of calcium, iron, etc.

Phys. Char. Commonly in octahedrons or grains, or cubes (***dysanalite***), or dodecahedrons (***koppite***). Cleavage absent or indistinct || 100 (*dysanalite*) or || 111 (*pyrochlore*). H. = 5.-6. G. = 4.13 (*dysanalite*), 4.2-4.36 (*pyrochlore*), 4.45-4.56 (***koppite***), 4.77-4.90 (***hatchettolite***), 5.1-5.4 (*pyrrhite*). Infusible, or difficultly fusible. Decomposed by sulphuric acid.

Opt. Prop. These minerals all have a very high index of refraction and show shagreen surfaces resembling that of titanite. ***Pyrochlore*** is reddish brown to golden yellow in transmitted light, usually completely isotropic; ***koppite*** is red to brown in section and isotropic; ***hatchettolite*** is brown to yellow and isotropic; ***pyrrhite*** is orange yellow to red in transmitted light and hyacinth red in reflected light, and isotropic; ***dysanalite*** is iron black with submetallic luster and opaque.

In mass the color is brown in ***pyrochlore***, hyacinth red in ***pyrrhite***, clear brown in ***koppite***, and opaque black in ***dysanalite***. Pyrochlore also occurs in crystals or grains with varying color—in zones of yellow and brown.

Occur. Found in nephelite syenite and alkaline granite, in pegmatite veins and in crystalline limestones. Very rare.

**PYROCHROITE**, see brucite. **PYROMORPHITE**, see apatite group. **PYROPE**, see garnet group. **PYROPHANITE**, see ilmenite group.

### PYROPHYLLITE.

Monoclinic? Axial ratio unknown $H_2Al_2Si_4O_{12}$

Phys. Char. Unknown in crystals; occurs in lamellar masses.

sometimes radiated or fibrous. Also found in cryptocrystalline masses resembling talc. Cleavage perfect || 001, giving flexible but inelastic lamellæ. H. = 1.-1.5. G. = 2.77-2.9. Difficultly fusible, often after much increase in volume. Partly decomposed by sulphuric acid.

Opt. Prop. The plane of the optic axes and the negative acute bisectrix are sensibly normal to 001; relief distinct; birefringence strong; optic angle large. Dispersion $\rho > v$ weak.

$$(-)\ 2E = 105°\text{-}110° \quad (2V = 62° \pm)$$

$$n = 1.58$$

$$n_g - n_p = 0.041$$

Colorless, white, yellowish, greenish. Colorless in thin section.

Occur. Found in some schistose rocks, occasionally making up the mass of the rock. Sometimes used to make slate pencils.

Diag. Distinguished from talc and muscovite by the large angle of the optic axes; distinguished from kaolinite by much stronger birefringence.

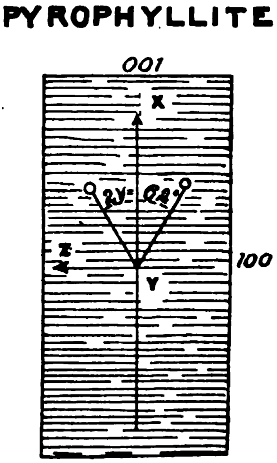

Figure 166.
Optical orientation of pyrophyllite.

**Pyroxene Group.**

The minerals of the pyroxene group are very closely related in crystallographic and other physical characters, as well as in optical characters and chemical composition, although they crystallize in three different systems (orthorhombic, monoclinic and triclinic). In all of them the fundamental and common form is a prism whose interfacial angles are about 87° and 93°, while parallel to both prism faces cleavages occur, which are distinct in all species. Chemically, the pyroxenes are metasilicates of calcium, magnesium or iron, or more complex silicates often containing two or more bases, both bivalent and trivalent.

Phys. Char. The pyroxenes commonly crystallize in prismatic forms, long or short. They have two good cleavages parallel to 110: and twinning, when present, usually has 100 as the twinning plane. H. = 5.-7. G. = 2.8-3.7. Fusibility 2-6. Insoluble, partly soluble, or soluble with gelatinization in acids.

Opt. Prop. The plane of the optic axes is parallel to 010 in the orthorhombic and monoclinic pyroxenes; the acute bisectrix is usually positive, and in the monoclinic pyroxenes makes a variable angle with the vertical axes in the obtuse angle 100∧001. See figure 167. These pyroxenes are sometimes elongated parallel to *c*, sometimes flattened parallel to 100. When

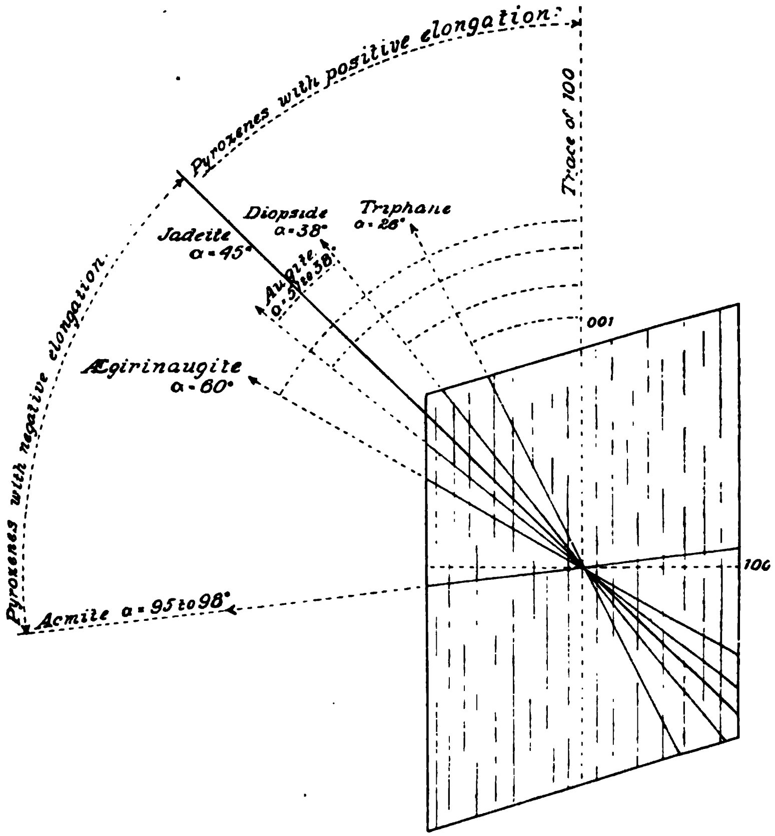

**Figure 167.** Diagram showing the position of the axis Z in the plane 010 in the monoclinic pyroxenes. Jadeite with $a = Z \wedge c = 33°$ and hedenbergite with $a = Z \wedge c = 45°$ to 48° are omitted.

parting occurs it is parallel to 100 or 001. The relief is always quite distinct, and the birefringence varies from 0.009 in enstatite to 0.029 in diopside and 0.052 in acmite. The angle of the optic axes is usually large (54° to 90°), but rarely it is very small.

Color black, green, brown, yellow, white, blue. In thin section usually pale to colorless, with pleochroism weak or absent. But soda pyroxenes have a distinct green color and pleochroism.

ALTER. Pyroxenes alter quite readily, especially to amphiboles. This, and other modes of alteration, will be described under the various species.

OCCUR. Pyroxenes are essential constituents of many igneous rocks, and occur in nearly all such rocks. They are also found in various metamorphic rocks, both regional and contact, and in meteorites.

DIAG. The pyroxenes may be distinguished from amphiboles as follows:—

| Pyroxenes | Amphiboles |
|---|---|
| Cleavage angle about 93° | Cleavage angle about 124° |
| Maximum extinction angle 0°-95°. (Common species 30°-54°) | Maximum extinction angle 0°-25° (Except arfvedsonite, etc.) |
| Most species positive | Most species negative |
| Color and pleochroism usually weak. | Color and pleochroism usually intense. |
| Crystals usually short prismatic. | Crystals usually long prismatic to fibrous. |
| Alter to amphiboles, etc. | Alter to chlorite, etc. (Change to pyroxene only through metamorphism). |

The pyroxenes may be classified as follows:—

ORTHORHOMBIC

|  | $a:b:c$ | or $a:b:c$* |  |
|---|---|---|---|
| Enstatite | 0.9702 : 1 : 0.5710 | 1.0307 : 1 : 0.5885 | $MgSiO_3$ |
| Bronzite |  |  | $(Mg.Fe)SiO_3$ |
| Hypersthene | 0.9713 : 1 : 0.5704 | 1.0319 : 1 : 0.5872 | $(Fe,Mg)SiO_3$ |

MONOCLINIC

|  | $a:b:c$ |  |  |
|---|---|---|---|
| Diopside | 1.0913 : 1 : 0.5895 | $\beta = 74° 9'$ | $CaMg(SiO_3)_2$ |
| Hedenbergite | 1.0912 : 1 : 0.5843 | $\beta = 74° 35'$ | $CaFe(SiO_3)_2$ |
| Augite | 1.0921 : 1 : 0.5893 | $\beta = 74° 10'$ | $m Ca(Mg,Fe)(SiO_3)_2$<br>$+ n(Mg,Fe)(Al,Fe)_2SiO_6$ |
| Spodumene | 1.1238 : 1 : 0.6355 | $\beta = 69° 40'$ | $LiAl(SiO_3)_2$ |
| Acmite | 1.0996 : 1 : 0.6012 | $\beta = 73° 11'$ | $NaFe(SiO_3)_2$ |
| Jadeite |  |  | $NaAl(SiO_3)_2$ |

TRICLINIC

Rhodonite $a:b:c :: 1.0729 : 1 : 0.6213$ $MnSiO_3$
$a = 103° 18'$ $\beta = 108° 44'$ $\gamma = 81° 39'$
Babingtonite $a:b:c :: 1.0691 : 1 : 0.6308$ $m(Ca,Fe,Mn)SiO_3 + nFe_2(SiO_3)_3$
$a = 104° 21'$ $\beta = 108° 31'$ $\gamma = 83° 34'$
Hiortdahlite $a:b:c :: 1.0583 : 1 : 0.7048$ $(Na_2,Ca)Fe[(Si,Zr)O_3]_2$
$a = 90° 29'$ $\beta = 108° 49'$ $\gamma = 90° 8'$

It is to be noted that pectolite and wollastonite are sometimes included with the monoclinic pyroxenes, but they differ from the latter in axial ratio, in cleavage, and in optical orientation; by Lacroix they are grouped with låvenite, mosandrite, johnstrupite, rinkite, rosenbuschite, and wöhlerite in an "annex" to the monoclinic pyroxenes.

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* The second set of axial ratios reverses the rule for orthorhombic crystals and makes the $a$ axis the longer lateral axis, but it thereby brings out clearly the close relation in form between these minerals and the other species of the pyroxene group.

## ENSTATITE.

ORTHORHOMBIC $a:b:c::0.9702:1:0.5710$ $MgSiO_3$
(or $a:b:c::1.0307:1:0.5885$)

PHYS. CHAR. Distinct crystals rare, prismatic. Usually massive, fibrous or lamellar. Twins rare; twinning plane either 014 or 101. Cleavage distinct || 110, parting often distinct || 010, less commonly || 100, rarely || 001. Enstatite rarely occurs wholly free from iron; varieties containing less than 5% FeO are called enstatite, from 5% to 14% bronzite, and more than 14% hypersthene. H. = 5.5. G. = 3.1-3.3. Fusible at 6. Insoluble in HCl.

OPT. PROP. The plane of the optic axes is parallel to 010; the positive acute bisectrix is normal to 001. The refringence and birefringence increase with the increase in the percentage of iron present. The optic angle about Z also becomes larger with the increase of iron. Dispersion $\rho < v$ weak.

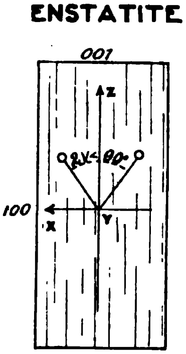

Figure 168. Optical orientation of enstatite.

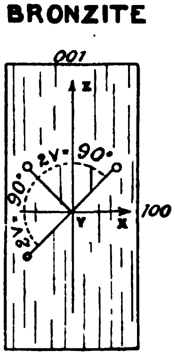

Figure 169. Optical orientation of bronzite.

| Enstatite 2.76% FeO | Bronzite 10% FeO | Hypersthene 22.6% FeO |
|---|---|---|
| (+) $2V = 69° 42'$ | (±) $2V = 90°$ about | (—) $2V = 72° 16'$ |
| $n_g = 1.665$ | | $n_g = 1.705$ |
| $n_m = 1.659$ | $n_m = 1.685$ about | $n_m = 1.702$ |
| $n_p = 1.656$ | | $n_p = 1.692$ |
| $n_g - n_p = 0.009$ | | $n_g - n_p = 0.013$ |

Color white, gray, yellow, brown, olive green; the darker colors belong to varieties containing more iron (bronzite). Enstatite is colorless in thin section; bronzite is colorless or nearly so; but in thick sections (about 1 mm.) bronzite is pleochroic, with Z = bright green, Y = brownish yellow, X = pale yellow.

INCL. Often contain gaseous or liquid inclusions which may be elongated parallel to the vertical axis of the pyroxene;

also vitreous inclusions, and inclusions of various other minerals, such as magnetite, apatite, etc. Bronzite also often contains inclusions regularly arranged which give it a submetallic bronze-like luster. See hypersthene for further description.

ALTER. Enstatite alters frequently through ordinary weathering to a variety of serpentine called *bastite*. Bastite is geometrically oriented on the altered pyroxene, and one crystal of bastite replaces a crystal of enstatite. The trace of easy cleavage of the two minerals is in the same direction, but the optic properties are different, the cleavage being parallel to the trace of the optic plane in the pyroxene and perpendicular to it and to the negative acute bisectrix in bastite. The refringence (1.5-1.6) of bastite is much less than that of enstatite. The birefringence is weak. The optic plane is parallel to 010; the positive acute bisectrix is normal to 001, (cleavage || 100). The optic angle is variable ($2E = 20°$ to nearly 90°). Dispersion $\rho > v$. Pleochroism weak in thick sections. In mass green or yellow with bronze-like luster.

Enstatite is much less commonly altered to uralite (variety of hornblende) than are the monoclinic pyroxenes. Its rarity is perhaps to be explained by the absence of alumina in enstatite; the fact that it occurs sometimes is in harmony with the fact that alumina (even 5%) sometimes occurs in enstatite.

Enstatite occurs rarely partly altered to talc; also to serpentine other than bastite; by fusion and recrystallization in nature it usually changes to augite.

OCCUR. Enstatite is a common constituent of many basic igneous rocks, as well as of serpentine rocks derived from them. It is also found in rocks produced by endomorphism; it is found in crystalline schists. Finally, it is an important constituent of many meteorites.

DIAG. Distinguished from hypersthene by optic sign and absence of distinct color and pleochroism; distinguished from monoclinic pyroxenes by parallel extinction on vertical sections and other characters resulting from orthorhombic symmetry.

## HYPERSTHENE.

ORTHORHOMBIC $a : b : c :: 0.9713 : 1 : 0.5704$ $(Mg,Fe)SiO_3$
or $a : b : c :: 1.0307 : 1 : 0.5872$

PHYS. CHAR. Distinct crystals rare, of prismatic habit, usually elongated || *c*; sometimes flattened || 100 or 010. Usually massive in lamellæ (common in peridotites, etc.) or cyclic forms; twins rare in stellate forms with 101 as twinning plane.

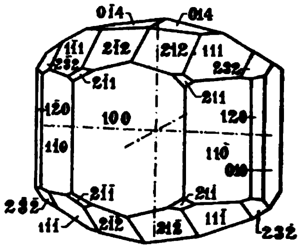

Figure 170. A crystal form of hypersthene.

Cleavage distinct || 110; parting || 010 usually very distinct in fine lines; rarely || 100. H. = 5.-6. G. = 3.3-3.5. Fusibility increases with increase of iron content; fusible to black enamel. Partly decomposed in HCl.

Opt. Prop. The plane of the optic axes is parallel to 010; the negative acute bisectrix is normal to 100. The refringence and birefringence increase with the increase in the percentage of iron present. The optic angle about X becomes smaller with the increase of iron. Dispersion $\rho > v$ weak.

| | % FeO = 15.1 | % FeO = 22.6 | % FeO = 28.4 |
|---|---|---|---|
| (—) $2V =$ | 81° 46′ | 72° 16′ | 70° 24′ |
| $n_g =$ | | 1.705 | |
| $n_m =$ | 1.695 | 1.702 | |
| $n_p =$ | | 1.692 | |
| $n_g - n_p =$ | | 0.013 | 0.015 (% FeO uncertain) |

**HYPERSTHENE**

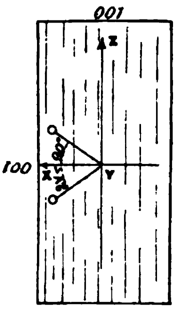

Figure 171. Optical orientation of hypersthene.

Color dark brown, grayish black, brown, yellowish brown. Luster often submetallic, and bronze-like on 010. In thin section color clear reddish or greenish with distinct pleochroism. The intensity of color or pleochroism increases with increase of iron. Absorption formula X > Y > Z. Pleochroic colors, in thin section from various occurrences:—

| | | |
|---|---|---|
| Z = bright green | pale green | bottle green |
| Y = yellowish brown | pale yellow | clear red |
| X = clear red | reddish yellow | brownish red |

Incl. Besides gaseous, liquid, and vitreous inclusions similar to those found in enstatite, hypersthene often contains reddish brown inclusions regularly arranged which give it a peculiar submetallic, bronze-like luster. These inclusions consist of lamellæ lying in 010 elongated either parallel or perpendicular to the vertical axis (less commonly making an angle of 30° with this axis). They are often approximately rectangular in outline in sections parallel to 010. They are supposed to be inclusions of ilmenite, either primary or produced when under pressure at depth by circulating waters acting along an easy cleavage or parting plane.

Alter. Hypersthene alters readily to *bastite* (see enstatite), less commonly to *uralite* (variety of hornblende), to talc, or rarely, to anthophyllite. By fusion and recrystallization in nature it is usually changed to augite.

OCCUR. Hypersthene with plagioclase makes up a large part of several granitoid basic igneous rocks, such as norites. It is also abundant in some andesites, less common in peridotites and pyroxenites; and found also in meteorites.

**Hypersthene-$\beta$** is an abnormal variety recently described by Lacroix. It has the same refringence as the normal variety with which it is intergrown, but it has the optic plane parallel to 001, and therefore the elongation is ±; the optic angle is large. A zone containing both varieties is isotropic. Found in basic volcanic rocks. Very rare.

DIAG. Distinguished from enstatite by the optic sign and the distinct color and pleochroism; distinguished from monoclinic pyroxenes by parallel extinction in vertical sections, and other characters resulting from the orthorhombic symmetry.

### DIOPSIDE and HEDENBERGITE.

MONO. $a:b:c::1.0913:1:0.5895$ $CaMg(SiO_3)_2$ to $CaFe(SiO_3)_2$
$\beta = 74° 9'$

PHYS. CHAR. Hedenbergite has an axial ratio practically the same as that given above for diopside, although iron replaces magnesium in the formula. Crystals usually short thick prisms with 100 and 010, or with 111, and the pinacoids absent or present. Often coarsely lamellar; rarely granular or fibrous. Twinning common; the twinning plane often || 100 giving polysynthetic lamellæ and secondary parting; also less often || 001 yielding very fine twinning lamellæ and parting; these latter can be produced artificially by pressure. Cleavage always distinct || 110; parting frequent || 100 (well developed in the variety *diallage*); sometimes || 010; also || 001 when twinning is present in this direction. H. = 5.-6. G. = 3.1-3.4 (diopside); 3.4-3.7 (hedenbergite. Fusibility 3.5 to nearly 4 (diopside), 2.5 (hedenbergite) decreasing with percentage of iron. Insoluble in HCl, only slowly soluble in hydrofluoric acid; much more easily attacked by HF than the orthorhombic pyroxenes.

OPT. PROP. The plane of the optic axes is parallel to 010; the positive acute bisectrix lies in the acute angle $\beta$ making an angle with the vertical axis (trace of the cleavage in vertical sections) which increases wth the amount of iron present. Further, the refringence varies in the same way from 1.68 to 1.73 with increasing iron, and the angle of the optic axes follows the same law, but the variation is small. Finally, the birefringence

**DIOPSIDE**

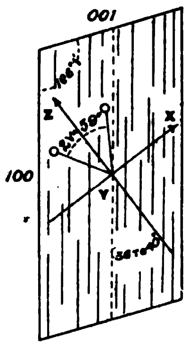

Figure 172.
Optical orientation
of diopside.

**HEDENBERGITE**

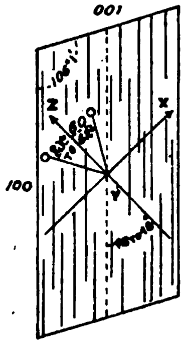

Figure 173.
Optical orientation
of hedenbergite.

decreases with the increase in iron percentage. This is shown in the following table.

| | Diopside | Salite | Hedenbergite |
|---|---|---|---|
| | 2.91% FeO | 17.34% FeO | 26.29% FeO |
| (+) $2V =$ | 59° | 60° | 60° |
| $n_g =$ | 1.7026 | 1.7271 | 1.7506 |
| $n_m =$ | 1.6798 | 1.7057 | 1.7366 |
| $n_p =$ | 1.6727 | 1.6986 | 1.7320 |
| $n_g - n_p =$ | 0.0299 | 0.0285 | 0.0186 |
| $Z \wedge c =$ | 38° | 45° | 48° |

Dispersion weak with $\rho > v$; distinct inclined dispersion of the bisectrices with the extinction angle greater (by 6′ to 12′) for red than for violet.

Color green, from nearly colorless to greenish black; also brown (diallage); in thin section, color and pleochroism become distinct with considerable iron present; diopside is usually colorless in thin section; hedenbergite is green, and diallage (often a variety of diopside with considerable iron) is green to brown. The pleochroic formulas for colored varieties are:

| Hedenbergite | Diallage |
|---|---|
| Z = dark green | greenish |
| X = yellowish green | greenish |
| Y = pale green | brownish or reddish brown |

Incl. Gaseous, liquid, and vitreous inclusions sometimes occur arranged in zones. Diallage has inclusions wholly like those of hypersthene and bronzite, yielding a bronze-like luster.

Alter. Diopside alters in many different ways; one of the commonest is the change to serpentine (antigorite), or to an aggregate of serpentine and chlorite, which often contains calcite and quartz, as well as grains of epidote. Another common alteration product is actinolite (or hornblende). This may be produced either by the alteration of one crystal of diopside to a single crystal of actinolite, or to a fibrous mass of amphibole. It may proceed by alteration around the periphery, or by attacking the diopside along cleavage lines. The green diopside of eclogite (called *omphacite*) alters similarly to a dark green hornblende called *smaragdite*. Other alteration products include biotite, feldspar, talc, calcite, quartz, opal, etc. When fused and recrystallized in nature augite usually results, sometimes with olivine and magnetite.

OCCUR. Diopside is an important constituent of some igneous rocks, such as pyroxene granite, diorite, certain rhyolites, syenites, pyroxenites, etc. It is abundant in some rocks produced by metamorphism, either regional or contact; it is in certain varieties an important element of some crystalline schists. Finally, it is found sparsely in some meteorites, and in some slags.

VARIETIES. Diopside proper corresponds very nearly to the formula $CaMg(SiO_3)_2$, and contains very little iron or alumina. *Salite* is a variety rich in iron (FeO) replacing magnesium, and thus furnishes a transition to *hedenbergite*, $CaFe(SiO_3)_2$. *Schefferite* is a variety containing 6% to 8% MnO; the extinction angle, $Z \wedge c$, varies from 44° to 69°. and $2V = 65°$; pleochroism weak in reddish yellow and brown tints. *Jeffersonite* is a variety containing about 10% each of MnO and ZnO; the extinction angle, $Z \wedge c$ is 53½° and $2H = 84½°$.

**Pigeonite.** The preceding varieties involve essentially a decrease in magnesium and no important change in calcium content. *Pigeonite* * is a variety with decreased calcium (only 8% to 10% CaO) and considerable magnesium and iron; it is optically remarkable by reason of its variable, but small, optic angle. Thus, while $2E = 110°$, or more, in the preceding varieties, and also in augite, and is essentially constant, the value of $2E$ in pigeonite equals only 13° to 67°, and is conspicuously variable, even in a single occurrence. (This variety is called magnesiumdiopside by Rosenbusch in the 1905 edition of his *Mikroskopische Physiographie*; this name is apparently an unfortunate selection, since the characteristic of the composition seems to be not increased magnesium but decreased calcium, often replaced by FeO.

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* See A. N. Winchell, *Amer. Geol.* Vol. XXVI, 1900, pp. 199-204.

and also because this name has been previously used for a pyroxene of different character found in meteorites). The extinction angle $Z \wedge c$ is perhaps equally variable with the optic angle. It has been reported as 7½°, 30° and 44°. The mineral sometimes has a parting || 001, or, more rarely, || 100; polysynthetic twinning occurs || 100. The refringence is high as in other pyroxenes, with $n_g = 1.711$, $n_m = 1.691$, $n_p = 1.690$; $n_g - n_m = 0.022$ to $0.020$, $n_m - n_p = 0.001$ to $0.004$, $n_g - n_p = 0.021$ to $0.023$. The color is variable from colorless to pale green and pink, with Z pale green, Y pale yellowish green, X pink or flesh colored. Found in diabase, gabbro, etc. in widely separated localities.

W. Wahl[*] (*Tsch. Min. Pet. Mitt. Bd.* XXVI. p. 1-131. 1907) considers that the existence of pyroxenes of small optic angle is due to the existence of two end compounds (monoclinic $MgSiO_3$ and $FeSiO_3$) in which the optic plane is normal to 010, and the optic angle is large. He considers that these compounds enter into isomorphous mixtures with ordinary diopside and augite molecules for which the optic plane is parallel to 010. In such a series, (not necessarily continuous) of isomorphous compounds the optic angle would necessarily be variable, passing through zero.[**] These compounds would belong to what Wahl calls "the *enstatit-augite series,*" previously named pigeonite, as already described.

**Malacolite** is a variety of diopside with a parting well developed || 001; it does not differ chemically from ordinary diopside. **Diallage** is a variety showing well developed parting || 100 (rarely || 010); it may contain considerable alumina and is then a variety of augite. **Chrome diopside** contains some $Cr_2O_3$ (1-3%) and some $Al_2O_3$ (1-7%); it is emerald green in color. **Omphacite** is a variety also containing $Al_2O_3$ (5-9%), of a green color occurring in eclogites. These minerals emphasize the gradual natural gradation existing between diopside and augite.

DIAG. Diopside is distinguished from other monoclinic pyroxenes as follows:—it differs from augite in the absence or scarcity of alumina; further, diopside has less dispersion than most augite and therefore better extinction in white light; it differs from acmite and spodumene in the extinction angle in the vertical zone; jadeite is always fibrous, is not known to occur in Europe or America in place, and contains abundant sodium.

## AUGITE.

MONOCLINIC. $a:b:c::1.0921:1:0.5893$ $m\mathrm{Ca(Mg,Fe)(SiO_3)_2}$
$\beta = 74°\ 10'$ $+n\mathrm{(Mg,Fe)(Al,Fe)_2SiO_6}$

PHYS. CHAR. Crystals usually short thick prisms; often coarsely lamellar || 001 or 100; also granular; rarely fibrous. Twinning common; the twinning plane often || 100 giving polysynthetic lamellæ and secondary parting; also less often || 001 yielding very fine twinning lamellæ and parting, which can be produced artificially by pressure; twinning plane rarely 101, also $\bar{1}22$ or 011 producing cruciform twins. Cleavage nearly always distinct || 110; parting frequent || 100; also || 001 when twinning is present in this position. H. = 5.-6. G. = 3.2-3.6. Fusibility about 3, varying with the composition. Only very slowly attacked by hot HCl (but titanaugite is completely soluble); much more easily attacked by HF than the orthorhombic pyroxenes.

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[*] Wahl's statements that pyroxenes of small optic angle are found only in diabases, and that they are characterized by the ratio $CaO : FeO + MgO :: 1 : 6$ do not seem to be justified by the facts observed in the Lake Superior region.

[**] See also H. Backlund: *T. M. P. Mitth.* XXVI, p. 357. 1908.

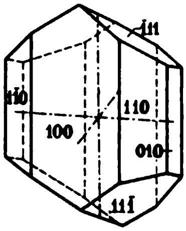

Figure 174. Simple crystal form of augite.

Opt. Prop. The plane of the optic axes is parallel to 010; the positive acute bisectrix lies in the obtuse angle $\beta$ making an angle of 38° to 54° with the vertical axis (trace of the cleavage in vertical sections). Refringence high and birefringence rather strong. The angle of the optic axes varies with the composition from about 60° to 61° (rarely more, up to 68°).

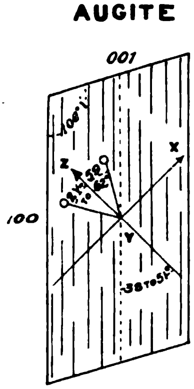

Figure 175. Optical orientation of augite.

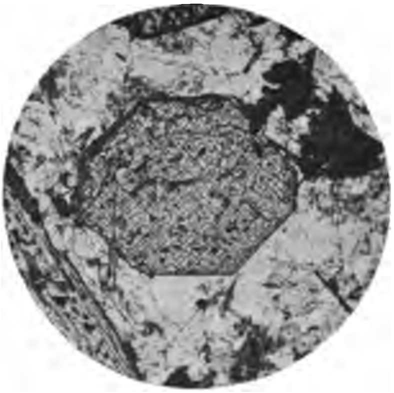

Figure 176. Cross section of pyroxene showing crystal form and prismatic cleavage, as found in theralite from Pine Creek Butte, Crazy Mts., Mont. H. 566.1. One nicol. × 45.

Dispersion weak with $\rho > v$; distinct inclined dispersion of the bisectrices with the extinction angle in the vertical zone less (by about 1°) for red than for violet.

| | Auvergne | Auvergne | Renfrew, Ont. |
|---|---|---|---|
| (+) $2V =$ | 60° | ? | 61° |
| $n_g =$ | 1.733 | 1.728 | 1.7227 |
| $n_m =$ | 1.717 | 1.712 | 1.7039 |
| $n_p =$ | 1.712 | 1.706 | 1.6975 |
| $n_g - n_p =$ | 0.021 | 0.022 | 0.0252 |

Color green, greenish black, brown, brownish black; rarely grayish green or yellow. In thin section pleochroism usually absent or very weak; when rich in iron, titanium, or sodium augite shows distinct pleochroism as follows:—

| | Ferriferous augite | Titanaugite | Ægirinaugite |
|---|---|---|---|
| Z = | greenish | greenish yellow or reddish (or violet) | brownish yellow or greenish |
| Y = | brownish to reddish brown | red or violet | clear green |
| X = | greenish | greenish yellow or reddish | dark grass green |

Incl. Gaseous, liquid, and vitreous inclusions sometime occur arranged in zones. Diallage has inclusions wholly like those of hypersthene and bronzite.

Alter. Augite has many different alteration products; the commonest is probably the change to *uralite* (variety of hornblende). This may occur so that a single crystal of augite yields a single crystal of uralite, or it may yield a fibrous aggregate of uralite, sometimes with feldspar. The alteration may begin around the periphery, or it may proceed along the cleavage lines of the augite. Another common alteration product is antigorite (variety of serpentine), which may be fibrous or lamellar. Again, augite may alter to biotite, and then that may change to chlorite, or the pyroxene may alter directly to chlorite. In such cases, calcite, quartz and epidote may be formed at the same time. Occasionally a crystal of augite may be changed wholly to calcite, or to quartz. By fumarolic action pyroxene may be changed to opal and quartz. When fused and recrystallized in nature augite usually forms again, sometimes with olivine and magnetite.

**Fassaite** may be used to designate those light colored varieties of augite which contain little iron. Fassaite therefore resembles diopside very closely; it usually shows very weak pleochroism in colors like ferriferous augite; the angle of the optic axes is a little smaller than in other varieties of augite or in diopside, $2V$ being 50° to 60°. The extinction angle in the vertical zone is about 40° to 45°. Dispersion weak, both of the axes and of the bisectrices, but the extinction angle is slightly less for red than for blue.

**Ferriferous augite** (or **basaltic augite**) is usually dark colored and pleochroic, as shown above; the extinction angle is 45° to 54°; the dispersion is distinct with $\rho < v$, and the extinction angle is distinctly less for red than for blue. As a consequence, complete extinction is not obtained in sections || 010 in white light.

**Titanaugite** contains $TiO_2$ up to about five per cent.; it has a peculiar reddish or violet color with pleochroism as indicated above; dispersion of the axes strong, with $\rho < v$, and dispersion of the bisectrices also strong; with the extinction angle less for red than for blue; therefore absence of complete extinction is particularly noticeable.

**Aegirinaugite** contains $Na_2O$ in important amount and thus grades toward acmite (or ægirine). The angle of the optic axes is probably larger than in other augites, but exact measurements are lacking. The extinction angle in the vertical zone is 60° to 80°. Dispersion notable with incomplete extinction. Color and pleochroism distinct, as already given. Refringence high, birefringence strong; $n_g = 1.709$, $n_m = 1.687$, $n_p = 1.680$; $n_g - n_p = 0.029$.

**Diallage** with its abundant parting || 100 often contains considerable alumina, and is therefore often a variety of augite. **Omphacite** likewise may contain alumina.

OCCUR. Augite is especially abundant in igneous rocks, and diopside in crystalline schists, but neither is confined to such occurrence. Augite is found in various metamorphic rocks, including some schists; it is found in igneous rocks of very many types, including most of the common classes. It is found also in some slags, and in some stony meteorites.

DIAG. Augite differs from diopside in containing considerable alumina; it also (except fassaite) has more dispersion than diopside, and therefore gives incomplete extinction in white light; finally, the maximum extinction angle in the vertical zone in augite is less for red than for violet, and in diopside it is greater for red than for violet. Augite differs from acmite and spodumene in the extinction angle in the vertical zone, while jadeite is always fibrous, and contains abundant sodium.

## SPODUMENE (Triphane).

MONOCLINIC $a:b:c::1.1238:1:0.6355$ $LiAl(SiO_3)_2$

$\beta = 69° 40'$

PHYS. CHAR. Crystals prismatic, sometimes flattened || 100; vertical faces striated. Usually in cleavable masses. Twinning plane || 100. Cleavage distinct || 110; parting || 010, more rarely || 100. H. = 6.-7. G. = 3.1-3.2. Fuses at 3.5 after turning white, swelling and giving a purple red flame color (Li). Insoluble in acids.

OPT. PROP. The plane of the optic axes is parallel to 010; the positive acute bisectrix makes an angle of about 26° with $c$ in the obtuse angle $\beta$. The optic angle is large; refringence marked, and birefringence moderate. Dispersion $\rho < v$ weak.

$$(+)\ 2V = 54° \text{ to } 60°$$

$$n_g = 1.677 \quad n_m = 1.669 \quad n_p = 1.651$$

$$n_g - n_p = 0.026$$

Color white, yellowish, greenish, emerald green (hiddenite), pink. Usually colorless in thin section, with very weak pleochroism in thick crystals in green tints. Varieties with distinct color (hiddenite and kunzite) have pleochroism in thin section, as follows:—

| | Kunzite | Hiddenite |
|---|---|---|
| Z = | colorless | colorless* |
| Y = | pink or amethystine | greenish |
| X = | amethystine purple | green |

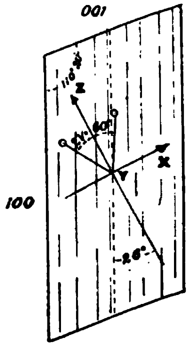

Figure 177.
Optical orientation of spodumene.

ALTER. Spodumene at Goshen, Ct. alters to a fibrous mass of eucryptite and albite; a later stage in the alteration results in the formation of a mass of muscovite and albite; still later, the albite changes to microcline. This alteration is nothing more than a progressive replacement of lithium by potassium.

OCCUR. Found in pegmatite of granite, gneiss, and micaschist; more rarely in normal granite and gneiss. Rare.

DIAG. Distinguished from other monoclinic pyroxenes by the extinction angle in the vertical zone, by the mode of occurrence, and by the presence of lithium.

## ACMITE (Ægirine).

MONOCLINIC $a:b:c::1.0996:1:0.6012$ $NaFe(SiO_3)_2$

$\beta = 73° 11'$

PHYS. CHAR. Crystals long prismatic, vertically striated. Acute terminations characteristic of *acmite*, obtuse terminations of *aegirine*. Also occurs in groups of slender acicular crystals and in fibrous tufts. Twinning || 100 common in *acmite*, uncommon in *aegirine*. Cleavage || 110 more distinct than in augite; parting sometimes easy || 010, also || 001. H. = 6.-6.5. G. = 3.5-3.55. Fuses at 2 to black magnetic globule, giving deep yellow flame color. Only slightly attacked by acids.

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* Hiddenite is pleochroic in green tints, but the pleochroic formula is not known; it is inferred above to have the same absorption formula as kunzite.

Opt. Prop. The plane of the optic axes is parallel to 010; the negative acute bisectrix makes a small angle (about 5°) with the vertical axis (trace of cleavage in vertical sections) in the acute angle $\beta$; therefore Z makes an angle of about 95° with the vertical axis. The optic angle is large; the refringence high and the birefringence quite strong. Dispersion distinct with $\rho > v$, and extinction angle in the vertical zone less for red than for blue. Therefore extinction is quite incomplete in white light.

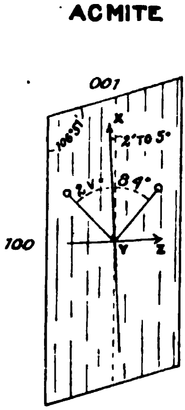

Figure 178. Optical orientation of acmite.

| | Na | Tl |
|---|---|---|
| (—) $2V$ = | 62°13′ | 61°44′ |
| $n_g$ = | 1.8126 | 1.8238 |
| $n_m$ = | 1.7990 | 1.8096 |
| $n_p$ = | 1.7630 | 1.7714 |
| $n_g - n_p$ = | 0.0496 | 0.0524 |

Color of acmite reddish brown to black, of ægirine green to black; in thin section brownish or greenish, with absorption formula X>Y>Z, and pleochroic formulas:—

| | Acmite | Ægirine |
|---|---|---|
| Z = | greenish to brownish yellow | yellowish green |
| Y = | yellow to greenish yellow | olive green |
| X = | greenish to dark brown | dark grass green |

Alter. Acmite alters to iron oxides, and also to analcite.

Occur. Found in pegmatite veins, in nepheline syenites, in phonolites, and in augite syenite. *Acmite* is supposed to have a little more iron than *aegirine,* but the two are practically identical.

Diag. Distinguished from other monoclinic pyroxenes by the very small extinction angle, the negative sign and elongation, the strong birefringence, and marked pleochroism; further, the density is greater, and the fusibility less.

## JADEITE.

Monoclinic Axial ratio unknown. $NaAl(SiO_3)_2$

Phys. Char. Unknown in crystals; usually in fibrous to acicular forms often interlaced so as to be quite compact. Cleavage distinct || 110; parting indistinct || 100. H. = 6.-7. Very tenacious. G. = 3.3-3.5. Fuses readily to transparent yellowish or grayish glass. Not attacked by acids.

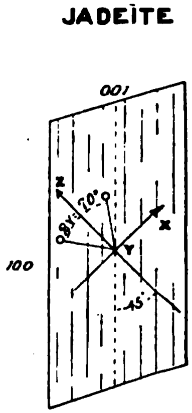

Figure 179.
Optical orientation of jadeite.

Opt. Prop. The plane of the optic axes is parallel to 010; the positive acute bisectrix makes an angle of 31° to 35° with the vertical axis (trace of cleavage in vertical sections). The optic angle is large; refringence high; birefringence strong. Weak inclined dispersion with $\rho > v$.

$$(+) \quad 2V = 71° \, 56'$$
$$n_m = 1.654$$
$$n_g - n_p = 0.029$$

Color apple green to emerald green; greenish white, colorless; in thin section, colorless.

Alter. **Chloromelanite** is apparently an alteration product of jadeite. It has all the optic properties of jadeite; it contains more iron than the latter mineral and is therefore darker colored. It seems to alter to smaragdite.

Occur. Occurs in Burmah, southern China, and Thibet; not certainly known in place in Europe or America. Found in both these continents and elsewhere with relics of early man, who worked it into various ornaments and utensils.

**Percivalite*** seems to be a variety of jadeite colored light green by the presence of a little isomorphous acmite; in thin section the pleochroic colors are those of acmite, but paler, while the extinction angle is about 7°.

Diag. Distinguished from other monoclinic pyroxenes by larger optic angle, fibrous habit, the smaller extinction angle (acmite and ægirinaugite have still smaller or similar extinction angles, but in them the elongation is negative,) the mode of occurrence, and the presence of abundant sodium and aluminum.

## RHODONITE.

Triclinic. $a:b:c::1.0729:1:0.6213$ $MnSiO_3$

$$\alpha = 103° \, 18' \quad \beta = 108° \, 44' \quad \gamma = 81° \, 39'$$

Phys. Char. Crystals usually rough and tabular || 001; often elongated || 110 or $1\bar{1}0$. Commonly massive, cleavable to compact; also granular. Also lamellar or fibrous. Cleavage perfect || 110 and $1\bar{1}0$. Easy || 001. H. = 5.5-6.5. G. = 3.4-3.68. Blackens and fuses with slight intumescence at 2.5. Slightly attacked by acids.

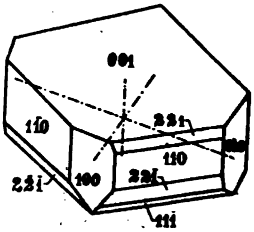

Figure 180.
A simple crystal form of rhodonite.

Opt. Prop. The plane of the optic axes makes angles of 63° with $1\bar{1}0$ and 38½° with 001; the negative acute bisectrix is normal to a plane making angles of 51° 40′ with 001 and 51° 47′ with 110; the obtuse bisectrix is normal to a plane making angles of 86° 55′ with 001

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* S. Weidman, G. N. H. S. Wis. Bull. XVI. p. 283.

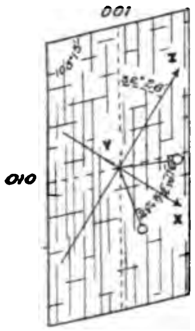

Figure 181.
Optical orientation of rhodonite in a macropinacoidal section.

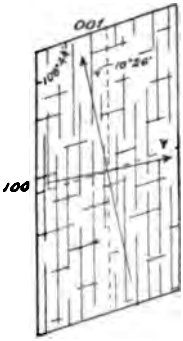

Figure 182.
Optical orientation of rhodonite in a brachypinacoidal section.

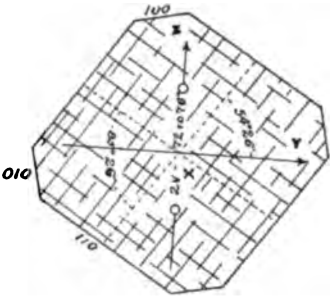

Figure 183.
Optical orientation of rhodonite in a basal section.

and 50° 7′ with 1$\bar{1}$0. Refringence high; birefringence rather weak; optic angle large. Marked crossed dispersion with $\rho < v$ weak.

$$(-)\ 2V = 76°\ 12'$$
$$n_m = 1.73$$
$$n_g - n_p = 0.010 \text{ to } 0.011$$

Color reddish brown, pink, yellowish or greenish gray; brown to black by alteration. Colorless in thin section, but in thick plates: Z = clear pinkish red, Y = pinkish red, X = clear reddish yellow.

**Alter.** Alters often by weathering to pyrolusite; also changes to rhodochrosite, which in turn alters to black manganese oxide.

**Occur.** Found in iron ore deposits, and in veins containing manganese and other metals.

**Diag.** Distinguished from other pyroxenes by the crystal system which leads to extinction always inclined; also by the richness in manganese.

## BABINGTONITE.

**Triclinic** $a:b:c::1.0691:1:0.6308$ $m(\text{Ca,Fe,Mn})\text{SiO}_3 + n\text{Fe}_2(\text{SiO}_3)_3$
$\alpha = 104°\ 21'$ $\beta = 108°\ 31'$ $\gamma = 83°\ 34'$

**Phys. Char.** Crystals small with striated faces. Form similar to augite. Cleavage perfect || 1$\bar{1}$0, less perfect || 110. H. = 5.5-6. G. = 3.36. Fuses at 2.7 to black magnetic globule. Not attacked by acids.

**Opt. Prop.** The plane of the optic axes seems to be nearly parallel to 110; it is nearly normal to $1\bar{1}0$; the extinction angle in 100 is 44°, and in 010 31°. Birefringence strong; optic angle large. Dispersion very marked.

$$(+)\ 2V = 60° \text{ to } 65°$$
$$n = 1.72$$
$$n_g - n_p = 0.032$$

Color greenish black. Pleochroism intense even in thin section, as follows:—

| | |
|---|---|
| Z = dark brown | dark grass green |
| Y = pale violet brown | yellow |
| X = very dark emerald green | clear green |

Occur. Found in cavities in granite; in syenite, in mica slate or gneiss. Often associated with epidote and garnet. Also found as a furnace product. Rare.

Diag. Distinguished from other pyroxenes by triclinic character, marked dispersion, and intense pleochroism as shown above.

## HIORTDAHLITE.

Triclinic $a:b:c :: 1.0583:1:0.7048$ $(Na_2,Ca)Fe(Si,Zr)_2O_6$
$\alpha = 90° 29'$ $\beta = 108° 49'$ $\gamma = 90° 8'$

Phys. Char. Crystals tabular || 100 and elongated || *c;* polysynthetic twinning lamellæ with *c* as twinning axis and 100 as composition face. Cleavage indistinct parallel to the prism faces, nearly at right angles; in traces || 010. H. = 5.-6. G. = 3.27. Fuses easily to yellowish white enamel. Gelatinizes with acids.

Opt. Prop. The plane of the optic axes is nearly parallel to $\bar{1}\bar{1}1$; the acute bisectrix is situated in the upper left hand front octant, the optic normal in that behind. The plane of the optic axes, as indicated by the extinction, makes angles with *c* of 65° in 100 and 74½° in 010. Optic angle large; refringence high; birefringence weak.

$$(+)\ 2V = \text{large}$$
$$n = 1.68\text{-}1.71$$
$$n_g - n_p = 0.0123$$

Color light yellow to yellowish brown. Pleochroism usually invisible in thin section; in thick sections Z = wine yellow, Y = yellowish white, X = almost colorless.

Occur. Known only in nepheline syenite from Sweden. Rare.

**Hainite** is a related triclinic silicate of sodium, calcium, possibly cerium, with titanium and zirconium. Crystals acicular, prismatic. Twinning on 100. Cleavage rather distinct || 010, indistinct || 100. H. = 5.±. G. = 3.18. Acute bisectrix Z nearly normal to 010. Extinction on 100 nearly parallel trace of 010, on 010 about 4° from trace of 100; in section normal to *c* about 16.5° from trace of 100. Extinction imperfect on account of strong dispersion of the bisectrices, with $\rho > v$. $2E$ large. Refringence high, about 1.7; birefringence not more than 0.012. Color and pleochroism like hiortdahlite. Found in phonolite in Bohemia. Very rare. Differs from hiortdahlite optically in having positive elongation; elongation in the latter is ±.

Diag. Distinguished from wöhlerite and låvenite by the weak birefringence, from rinkite and johnstrupite by the lack of good cleavage, and from all these minerals by the crystal system.

**PYRRHITE,** see pyrochlore group. **PYRRHOTITE,** see cinnabar group. **PYROSMALITE,** see friedelite. **PYROSTILPNITE,** see pyrargyrite.

## QUARTZ.

HEXAGONAL $c = 1.09997$ $SiO_2$

PHYS. CHAR. Crystals usually prismatic, terminated by two rhombohedrons $10\bar{1}1$ and $01\bar{1}1$. Sometimes in double six-sided pyramids made up of two rhombohedrons. Crystals also highly modified, and distorted. Horizontal striations common on prismatic faces. Massive forms common from coarse to fine granular or even to crypto-crystalline. Simple crystals are uncommon; usually twinned by interpenetration, the twinning axis often the vertical axis, and in this case the twins may be united so as to be symmetrical with respect to 0001 or $10\bar{1}0$ or $11\bar{2}0$. Much more rarely other twinning laws occur, thus, the twinning plane may be $11\bar{2}2$. Cleavage nearly always absent or very difficult; cleavage may be obtained by sudden cooling or by pressing with a needle on a thin section. Cleavage difficult || $10\bar{1}1$ and $01\bar{1}1$, in traces || $10\bar{1}0$ and 0001. H. = 7. G. = 2.653-2.654. Infusible. Insoluble in acids except in HF; difficultly attacked by alkalies.

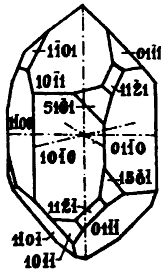

Figure 184.
A simple crystal form of quartz.

OPT. PROP. Uniaxial and positive. Refringence low; birefringence weak. Rotary polarization (invisible in thin sections) increasing with the thickness of the section. Right-handed and left-handed crystals equally common; the combination of these two produces the Airy spirals.

$$n_g = 1.55336 \quad n_p = 1.54425$$
$$n_g - n_p = 0.00911$$

The refringence decreases very slowly with increase of temperature; for fused quartz $n = 1.4588$. The birefringence likewise decreases slowly with increase of temperature, but only to 570° C.; above that temperature there is an abrupt change, and the birefringence thereafter increases.

Quartz occurs sometimes showing a distinctly biaxial character. In this case $2E = 12°-18°$, or, rarely, as much as 24°.

Color. Quartz is colorless in thin section, but often shows inclusions of various kinds which serve as pigments and give a color to thick sections and masses of the mineral. Thus quartz may be yellow, red, brown, green, blue, black. Quartz is not pleochroic. Streak colorless. Luster vitreous.

INCL. Liquid inclusions are especially characteristic of quartz. The liquid may be water, or $CO_2$, or both. Gaseous bubbles, sometimes movable, often accompany the liquid inclusions. These inclusions rarely occupy cavities which have the form of the enclosing mineral; such cavities are called negative crystals. Cubes, probably of NaCl, are sometimes found in these cavities. In other cases the liquid present is a carbide and causes the fetid odor of certain samples of quartz when struck a sharp blow.

The inclusions in quartz are usually arranged along lines, curved surfaces, or, sometimes, parallel to the crystal faces. They are occasionally very large, and visible to the naked eye. Other inclusions in quartz include reticulated rutile (*Venus' hair*), needles of tourmaline, of epidote, of actinolite or tremolite (when regularly arranged so as to produce opalescence these make the variety of quartz called *cat's eye*), of chlorite or of other slaty minerals. Transparent. Quartz containing reticulated or acicular rutile, or other mineral, is often called *sagenite.*

ALTER. Quartz is a very stable mineral; nevertheless, it occurs altered to talc, pyrite, cassiterite, magnetite, etc. Inversely, quartz is found in pseudomorphs after many minerals, notably calcite, fluorite, barite, etc. When fused in nature *embayments* are first formed, then the whole mass is fused. Upon recrystallization augite usually forms an aureole about that portion not completely fused. In acid rocks fused quartz recrystallizes at high temperatures as tridymite.

OCCUR. Quartz is one of the most abundant minerals found in nature; it is an essential constituent of rhyolite, granite, dacite, quartz diorite, gneiss, micaschist, and many related rocks. It is usually the chief, and often, nearly, the only, constituent of sandstone, gravel, conglomerate, and vein rocks. It occurs in less important amounts in many other igneous, metamorphic and sedimentary rocks. It is often deposited by hot springs and geysers.

In graphic granite skeleton crystals of quartz are arranged in parallel position in a very coarsely granitic aggregate of acid feldspar anhedra. In sandstone the grains are often enlarged by deposition about each one of quartz oriented upon the enclosed grain.

VARIETIES and related minerals. Some authors regard the hexagonal character of quartz as due to an intimate association of biaxial parts. This view finds support in the fact that fibrous silica is often biaxial. It is called **quartzine** when the fibers are elongated parallel to Z; the fibers of quartzine are sometimes grouped about a ternary axis so as to produce uniaxial quartz. Quartzine has a variable apparent angle of the optic axes on account of the superposition of fibers which is present in nearly all cases. It reaches 35° to 40°, if not more. The indices of refraction and the birefringence are very near those of quartz. Fibrous silica is called **chalcedonite** when the fibers are elongated parallel to X, and the elongation is therefore negative; furthermore, fibers of chalcedonite show all the possible gradations in birefringence, while fibers of quartzine always show the maximum birefringence; finally, in a single fiber of chalcedonite Z is always perpendicular to the elongation, but often changes its position continuously along the fiber so that its positions form a spiral about the fiber. Again, fibrous quartz is sometimes elongated || Y, and in this case the elongation is either positive or negative, but much more commonly negative, since $n_m$ and $n_p$ are not widely different in value. Lastly, fibrous quartz is called **lutécite** when it is elongated in the plane of Y and Z in a direction making an angle of about 29° with Z. Lutécite also forms characteristic groups about a senary axis resulting in pseudohexagonal crystals, basal sections of which are oblique to the acute positive bisectrix.

**Pseudochalcedonite** is the name given to fibrous silica, usually spherulitic, which is optically negative; the axis X is parallel with the elongation which is therefore negative. The angle of the optic axes is very small; the birefringence only half that of quartz, $n_g - n_p = 0.0045$ about; in other characters the mineral is closely like chalcedonite.

**Chalcedony** is a name given to megascopic forms of silica which are concretionary, fibrous or compact, and microcrystalline or cryptocrystalline. Opal is often present in large amounts in concretions of chalcedony, which may be made up of any of the preceding microscopic varieties. Chalcedony has various other names depending upon the color, structure, or other megascopic characters, such as carnelian, sardonyx, jasper, chrysoprase, agate, onyx, etc.

DIAG. The low refringence, weak birefringence and absence of color, cleavage or alteration usually serve to identify quartz. Distinguished from colorless fresh cordierite by the uniaxial character and lack of the twinning in the quartz. Other characters of importance include the specific gravity, hardness, crystal form, and resistance to acids, except HF.

**QUENSTEDTITE,** see coquimbite.

## REALGAR.

MONOCLINIC. $a:b:c::1.440:1:0.973$ AsS
$\beta = 66° \ 5'$

PHYS. CHAR. Crystals short, prismatic, vertically striated; coarse or fine granular; compact. Cleavage distinct || 010, 100, 110 and 210. H. = 1.5-2. G. = 3.56. Wholly volatile. Soluble in alkalies.

OPT. PROP. The optic plane is parallel to 010; the acute bisectrix X makes an angle of +11° with *c*. Birefringence strong; $n_\gamma - n_p = 0.030$. Inclined dispersion strong with $\rho > v$. $2H = 92° \ 58'$.

Color aurora red to orange yellow. Streak paler red. Luster resinous. In thin section distinctly pleochroic, with Z = Y vermilion red, X orange red.

ALTER. Changes on exposure to light to orpiment and arsenolite.

OCCUR. Found with silver and lead ores in veins; also in clay and in slate; often produced by solfataric action; also from geysers.

DIAG. Distinguished from orpiment by its inclined extinction and pleochroism, from cinnabar by its negative biaxial character and pleochroism.

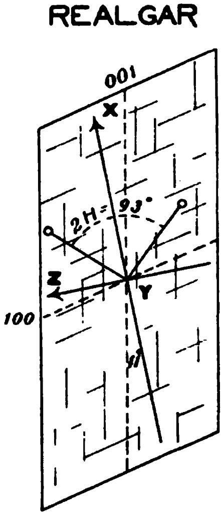

Figure 185.
Optical orientation of realgar.

**RHODOCHROSITE,** see calcite group. **RHODONITE,** see pyroxene group. **RICHTERITE,** see amphible group. **RIEBECKITE,** see amphibole group.

## RINKITE.

MONOCLINIC $a:b:c::1.5688:1:0.2922$ $Na_9Ca_{11}Ce_3(TiF_2)_4(SiO_4)_{12}$
$\beta = 88° \ 47'$

PHYS. CHAR. Crystals short columnar, or flattened || 100. Cleavage distinct || 100. Twinning common on 100, often producing several lamellæ. H. = 5. G. = 3.46-3.50. Fuses with intumescence to a black shining glass. Easily decomposed by dilute acids with separation of silica and titanic acid.

OPT. PROP. The plane of the optic axes and the obtuse bisectrix are normal to 010; the optic normal makes an angle of 7° with *c* apparently in the acute angle $\beta$. Relief moderate, birefringence also moderate. Strong dispersion with $\rho < v$; also distinct horizontal dispersion.

$$(+)\ 2V = 74°$$
$$n_g = 1.681 \pm \quad n_m = 1.6682 \quad n_p = 1.6654$$
$$n_g - n_p = 0.016 \text{ (calc.)}$$

Color yellowish brown to straw yellow. Pleochroism scarcely perceptible in thin section; in thick section Z = yellow, Y = yellowish white, X = colorless, with absorption $Z > Y > X$.

OCCUR. Found in nepheline syenite and related rocks, often associated with arfvedsonite, ægirite, lepidolite, fluorite, låvenite, etc. Rare.

DIAG. Distinguished from mosandrite by the position of the optic plane perpendicular to the plane of symmetry, and the strong dispersion $\rho < v$; differs from hiortdahlite in crystal system and cleavage.

**RIPIDOLITE,** see chlorite group.

## ROEMERITE.

TRICLINIC $a:b:c::0.968:1:2.643$ $FeFe_2(SO_4)_4 + 12H_2O$

$\alpha = 116° 4'$ $\beta = 94° 41'$ $\gamma = 80° 7'$

PHYS. CHAR. Crystals tabular || 001; coarsely granular. Cleavage perfect || 010. H. = 3.-3.5. G. = 2.1-2.17. Easily soluble in $H_2O$.

OPT. PROP. The trace of the optic plane in 001 bisects the obtuse angle between 100 and 010; the acute bisectrix X is inclined about 30° to *c*. $2H_a = 57° 45'$. Color brown to yellow.

OCCUR. Found with other iron sulphates. Very rare.

**ROSCOELITE,** see mica group (biotite).

## ROSENBUSCHITE.

MONOCLINIC $a:b:c::1.169:1:0.978$ $Na_2Ca_3[(Si,Zr,Ti)O_3]_4$

$\beta = 78° 13'$

COMP. Fluorine is commonly present in notable amount: manganese and cerium in smaller amount.

PHYS. CHAR. Crystals elongated || *b* with 001, 100, $\bar{2}01$, and rarely 540 present. In radiating groups or felt-like. Cleavage perfect || 001, imperfect || 100 and $\bar{2}01$. H. = 5.-6. G. = 3.3-3.32. Easily fusible. Soluble in HCl.

OPT. PROP. The optic plane and the bisectrix X are normal to 010; the bisectrix Z makes an angle of 12° to 14° with *c* in the acute angle $\beta$. Optic angle large; optic sign uncertain; Broegger considers it probably positive.

$$2V = \text{large}$$
$$n = 1.65 \pm$$
$$n_g - n_p = 0.026$$

Color light orange gray. Luster vitreous. In thin section colorless to pale yellowish with slight pleochroism and distinct absorption, $Z > Y > X$.

OCCUR. Found in nepheline syenite. Rare.

DIAG. Rosenbuschite has negative elongation, while wollastonite has positive or negative elongation, and pectolite, sillimanite, and carpholite have negative elongation.

### Rutile Group.

The minerals of the rutile group are oxides of tetravalent acid elements, or metals which act sometimes as acid elements. They are tetragonal and have closely similar forms and the same twinning laws. So far as known the optic properties are also very similar; all are uniaxial and positive, have very high refringence and extremely strong birefringence.

The minerals of the group are the following:—

| | | |
|---|---|---|
| Rutile | $c = 0.6441$ | $TiO_2$ |
| Zircon | $c = 0.6404$ | $(Zr,Si)O_2$ |
| Thorite | $c = 0.6402$ | $(Th,Si)O_2$ |
| Cassiterite | $c = 0.6723$ | $SnO_2$ |
| Plattnerite | $c = 0.6764$ | $PbO_2$ |
| Polianite | $c = 0.6647$ | $MnO_2$ |

### RUTILE.

TETRAGONAL $c = 0.6441$ $TiO_2$

PHYS. CHAR. Crystals nearly always elongated || $c$, sometimes finely fibrous. Rarely elongated || 111. Crystals vertically striated. Twinning || 101 frequent in macroscopic crystals; this type is known as geniculated twinning when composed of two parts; when composed of several parts it may be arranged in a cycle of six or eight, or it may form lamellæ visible microscopically in basal sections. Twinning also on 301, rare in large crystals, but commonly found in microscopic size. Twinning on 902 is always polysynthetic and accompanied by parting planes. The reticulated groups in sagenite, etc., are usually due to a combination of these two twinning laws. Cleavage easy || 100 and 110. H. = 6.-6.5. G. = 4.18-4.25. Infusible. Insoluble.

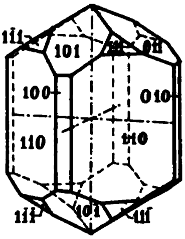

Figure 186.
A simple crystal form of rutile.

OPT. PROP. Uniaxial and positive. Refringence very high and birefringence extreme.

$$n_g = 2.9029 \quad n_p = 2.6158$$
$$n_g - n_p = 0.2871$$

Color red, reddish brown, brownish black, yellow, bluish, violet, rarely green. Streak pale brown. In thin section pleochroism often not noticeable. Sometimes it is distinct with X = yellow, or brownish red in a thick section, and Z = brownish yellow to yellowish green, or dark blood red to black in a thin section.

Rutile sometimes shows optic anomalies consisting of biaxial twinning bands crossing basal sections of the uniaxial mineral; in these bands the optic plane is || 110; the biaxial appearance is probably due to the combined effect of several twinning lamellæ at various angles.

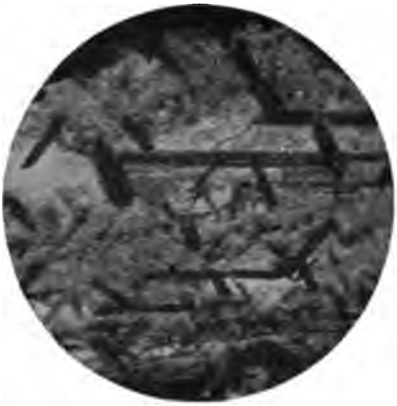

Figure 187. Section of rutile showing geniculated twinning and reticulations, in chlorite in quartz gabbro from Little Saganaga Lake, Minn. 854 G. One nicol. × 360.

Alter. Rutile is relatively a very stable mineral. Nevertheless, it is found to undergo various modifications in nature. One of the most common is the change to ilmenite. This is a process all of whose stages can be observed in various sections; the ilmenite forms about the borders and then along the cleavage lines of the rutile. In other cases rutile may be changed into titanite,—a process which is sometimes reversed.

Occur. Rutile is more widely distributed as a microscopic element of various rocks than as crystals of megascopic size. It is found in igneous rocks very widely distributed, but in such rocks it is much more commonly a result of alteration than a product of magmatic crystallization. It is very abundant in many metamorphic rocks, such as amphibolites, pyroxenites, gneiss, eclogites, etc. It is likewise common in some simple sedimentary rocks, and in rocks produced by contact or regional metamorphism from these. Finally, it is found in many veins, both metalliferous and non-metalliferous. It is then commonly associated with quartz, calcite, topaz, pyrite, sphalerite, etc.

Diag. Distinguished by reddish brown to yellow color, very high relief and extremely strong birefringence. Also characterized by brilliant luster, distinct tetragonal cleavages, and high density.

## ZIRCON.

Tetragonal $c = 0.6404$ $(Zr,Si)O_2$

Phys. Char. Commonly in square prisms, usually elongated || $c$, and terminated by unit pyramids. Always crystallized. Twinning on 101 uncommon. Cleavage sometimes distinct || 110, indistinct || 111. G. = 4.68-4.70. H. = 7.5. Infusible. Slowly attacked when in fine powder by concentrated $H_2SO_4$.

Opt. Prop. Uniaxial and positive. Refringence very high; birefringence very strong.

$$n_g = 1.9832 \quad n_p = 1.9302$$
$$n_g - n_p = 0.053$$

Color yellow, brown, gray, rarely green or colorless. In thin section colorless to pale brown or gray. Pleochroism invisible in thin section, very weak in sections more than 1 mm. thick, with maximum absorption parallel to Z.

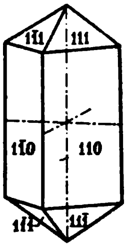

Figure 188. A simple crystal form of zircon.

Optical anomalies are unknown in the microscopic crystals, but appear in large crystals. Zonal structure is frequent in such cases. The mineral then appears biaxial and positive, with a small optic angle ($2V = 10°$; $n_g = 1.9820$, $n_m = 1.9277$, $n_p = 1.9272$; $n_g - n_p = 0.0548$ in olive green *beccarite* from Ceylon), the bisectrix being parallel to the quaternary axis. Mallard considers the common tetragonal symmetry to be due to twinning, often submicroscopic, of monoclinic individuals. The optic anomalies are perhaps due to alteration, being found especially in partly altered zircon.

Alter. Zircon resists alteration to a marked degree; but in some cases it becomes hydrous, and then the specific gravity falls rapidly from 4.7 to about 4.1, and the hardness decreases from 7.5 to about 3; at the same time the refringence decreases and the birefringence falls even more rapidly until it disappears entirely in *malacon* with only 3% $H_2O$. When the process continues further iron is often introduced as well as water. As illustrating this process we may tabulate recent results as follows, (values for zircon of density 4.33 are only approximate):—

| G. | $n_g$ | $n$ | $n_p$ | $n_g - n_p$ |
|---|---|---|---|---|
| 4.7 | 1.9682 | | 1.9239 | 0.044 |
| 4.33 | | 1.882 | | 0.034 |
| 4.06 | | 1.826 | | very weak |

Occur. Zircon is very widely distributed as an accessory constituent of igneous rocks of all kinds, but it is especially common in syenite, granite, nepheline syenite and diorite. It appears very sparingly in gabbro, peridotite, and theralite. It is apparently more abundant in plutonic than in volcanic rocks. It is also found in many kinds of metamorphic rocks, and by disintegration it reaches the sands and sediments.

It is one of the very earliest minerals to crystallize from a magma, and therefore it is found enclosed in many of the other rock minerals. When enclosed by micas (especially biotite) chlorite, cordierite, andalusite, sometimes amphiboles or pyroxenes it is surrounded by intense pleochroic halos.

DIAG. Zircon may be distinguished from cassiterite by much weaker birefringence, the mode of occurrence and chemical reactions; from xenotime by higher refringence, less perfect prismatic cleavage, greater hardness and chemical reactions; from thorite by much stronger birefringence, greater hardness, and insolubility in HCl.

## THORITE.

TETRAGONAL $c = 0.6402$ $(Th,Si)O_2$

PHYS. CHAR. In square prisms with pyramidal terminations. Forms like zircon. Also massive. Cleavage distinct || 110. H. = 4.5-5. G. = 5.2-5.4. Infusible. Gelatinizes before but not after calcination.

OPT. PROP. Uniaxial and positive. Becomes isotropic upon alteration.

Color orange yellow, brownish yellow, brownish black. Streak light orange to dark brown.

ALTER. Very rarely found unaltered. Upon alteration the specific gravity decreases to 4.8 or even 4.4, and the mineral becomes hydrous, amorphous, and isotropic.

OCCUR. Found in syenite in Scandinavia; also in Champlain iron district of northern New York. Rare.

DIAG. Usually amorphous and isotropic from alteration. Contains thoria.

## CASSITERITE.

TETRAGONAL $c = 0.672$ $SnO_2$

PHYS. CHAR. In short prismatic or pyramidal crystals, or in anhedra. Cleavage distinct || 100. Twinning as with rutile. H. = 6.-7. G. = 6.8-7.1.

OPT. PROP. Uniaxial and positive. The interference cross sometimes separates slightly into hyperbolas on rotation.

$$n_g = 2.093 \quad n_p = 1.997$$

$$n_g - n_p = 0.097$$

Color brown to black; also red, gray, yellow, white to almost colorless. Color sometimes irregularly distributed or in bands or zones. Luster adamantine. In thin section colorless, yellowish, brown, or reddish.

The pleochroism is of variable intensity in different localities; it is usually imperceptible in thin section; when most intense the colors are:—

Z = brownish yellow to black
X = golden yellow to iron gray

Occur. Usually produced by the action of mineralizers from acid granites in veins or in pegmatite. Also found in sulphide veins and in stream gravels.

Diag. Distinguished from rutile by its less extreme birefringence which produces bright colors, instead of the indefinite grays of the higher orders, in very thin sections.

**Plattnerite** ($PbO_2$) occurs rarely in crystals of prismatic habit; usually massive, sometimes globular. Cleavage unknown. H. = 5.-5.5. G. = 8.5. Fusible at 2. Soluble. Uniaxial and negative. Translucent to nearly opaque. Color iron black. Streak chestnut brown. Found in lead mines in Scotland and Coeur d'Alène district, Idaho. Rare. Distinguished from other minerals of the rutile group by mode of occurrence and negative sign.

**Polianite** is very rarely tetragonal in crystals which are minute and in groups; nearly always pseudomorphous after manganite (then called *pyrolusite*); often massive, encrusting. Cleavage perfect || 110. H. = 6.-6.5. Pyrolusite is soft because not compact. G. = 4.74-5.03. Soluble in HCl. Opaque. Color steel to iron gray. Luster metallic to earthy. A common surface ore of manganese. Found in veins, and in deposits, or disseminated in sedimentary rocks, commonly closely associated with manganite.

**SALMIAC,** see halite group.

## SAPPHIRINE.

Monoclinic $a:b:c::0.65:1:0.93$ $Mg_5Al_{12}Si_2O_{27}$

$\beta = 79° 30'$

Phys. Char. Crystals tabular || 010 rarely with prismatic planes. Also in lamellar aggregates, or in grains. No distinct cleavage. Twinning only microscopic. H. = 7.5. G. = 3.42-3.48. Infusible. Insoluble in acids; slowly attacked by calcium sulphate.

Opt. Prop. The plane of the optic axes is parallel to 010 and the axis Z makes an angle of 8° with $c$ in the acute angle $\beta$. The optic sign is negative. The optic angle is large. The relief is high and the birefringence very weak. Inclined dispersion very distinct with $\rho < v$.

$$(-)\ 2V = 68° 49' \ (2H = 77°\text{-}84°).$$
$$n_g = 1.7112 \quad n_m = 1.7088 \quad n_p = 1.7055$$
$$n_g - n_p = 0.0057$$

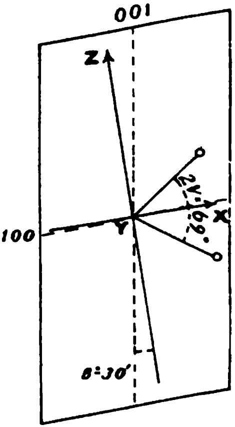

Figure 189.
Optical orientation of sapphirine.

Color pale blue or green. Pleochroism very weak in thin section in blue or green tints.

Z = pale blue    yellowish green
Y = pale blue    bluish green
X = colorless    pale greenish blue

OCCUR. Found in micaschists and gneiss in Greenland associated with green hornblende, pale brown mica, and gedrite; also cordierite, kornerupine and anorthite. Rare.

DIAG. Distinguished from corundum by the biaxial character, from lazulite by the weak birefringence, from cyanite, clintonites and blue amphiboles by the lack of cleavage, and from colored cordierite by the higher refringence.

## SARCOLITE.

TETRAGONAL    $c = 0.887$    $(Ca,Na_2)_3Al_2(SiO_4)_3$

PHYS. CHAR. Crystals small resembling cubo-octahedrons highly modified; related to scapolite. H. = 6. G. = 2.5-2.9. Fusible. Gelatinizes with acids.

OPT. PROP. Uniaxial and positive. Birefringence strong. Refringence $n = 1.64$. Color flesh red to rose red. Luster vitreous.

OCCUR. Found in ejected rock fragments at Vesuvius. Very rare.

**SARKINITE,** see flinkite.

## SASSOLITE.

TRICLINIC    $a : b : c :: 0.577 : 1 : 0.528$    $H_3BO_3$

$\alpha = 104° 17'$ $\beta = 92° 33'$ $\gamma = 89° 42'$

PHYS. CHAR. Crystals tabular || 001, nearly hexagonal in outline. Scaly; stalactitic. Twinning with *c* as twinning axis. Cleavage perfect || 001. H. = 1. G. = 1.48. Soluble in $H_2O$.

OPT. PROP. The optic plane is nearly parallel with *b;* the acute bisectrix X is slightly inclined to a normal to 001. Birefringence rather strong. Optic angle small. $2E = 10° - 12°$. $n = 1.46$. No visible dispersion. Color white or grayish. Luster pearly. Colorless in section.

OCCUR. Found in Tuscan lagoons; also a fumarolic product. Rare.

### Scapolite Group.

The minerals of the scapolite group are silicates of aluminum with calcium or sodium, or both, usually containing more or less chlorine. They crystallize in the tetragonal system with very similar forms. The hardness varies from 5.-6.5, and the specific gravity from 2.5 to 2.8.

The scapolites, like the feldspars, form a series with a gradual variation in composition and in physical characters. The silica increases with the increase in soda; chlorine increases at the same time. Further, the specific gravity decreases, the solubility in acids decreases, and the refringence and birefringence diminish as the silica increases.

The composition may be explained by the isomorphous combination of two molecules, namely the meionite molecule $Ca_4Al_6Si_6O_{25}$(Me) and the marialite molecule $Na_4Al_3Si_9O_{24}Cl$ (Ma). The minerals may then be classed as follows:—

| | | |
|---|---|---|
| Meionite | $c = 0.4393$ | $Me_1Ma_0$ - $Me_4Ma_1$ |
| Wernerite | $c = 0.4384$ | $Me_3Ma_1$ - $Me_1Ma_1$ |
| Dipyre | $c = 0.4424$ | $Me_1Ma_2$ - $Me_1Ma_3$ |
| Marialite | $c = 0.4417$ | $Me_1Ma_4$ - $Me_0Ma_1$ |

## MEIONITE.

TETRAGONAL $c = 0.4393$ $Me_1Ma_0$ to $Me_4Ma_1$

PHYS. CHAR. Crystals short prismatic with pyramidal terminations. Also granular and massive. Cleavage distinct || 100 and 010, less distinct || 110. H. = 5.5-6. G. = 2.70-2.74. Fusible with intumescence at 3. Decomposed by acids without gelatinization.

OPT. PROP. Uniaxial and negative. Refringence considerable; birefringence strong; both decrease with increase of the proportion of marialite present.

$$n_g = 1.597 \text{ to } 1.583$$
$$n_p = 1.560 \text{ to } 1.552$$
$$n_g - n_p = 0.037 \text{ to } 0.031$$

Colorless to white. Colorless in section.

INCL. and ALTER. Similar to dipyre.

OCCUR. Found in small crystals in cavities usually in limestone blocks at Vesuvius; also in crystalline schist and gneisses. Not common.

DIAG. Distinguished from other scapolites by higher relief and stronger birefringence; also by the scarcity or absence of sodium and chlorine. See also wernerite.

## WERNERITE.

TETRAGONAL $c = 0.4384$ $Me_3Ma_1$ to $Me_1Ma_1$

PHYS. CHAR. Crystals often coarse, rough and large. Also massive. Cleavage distinct but interrupted || 100 and 010. less distinct || 110. H. = 5.-6. G. = 2.66-2.70. Fuses easily with intumescence. Imperfectly decomposed by HCl.

OPT. PROP. Uniaxial and negative. Refringence considerable; birefringence rather strong; both decrease with increase in the proportion of marialite present.

$$n_g = 1.583 \text{ to } 1.563$$
$$n_p = 1.553 \text{ to } 1.545$$
$$n_g - n_p = 0.030 \text{ to } 0.018$$

Color white, gray, bluish, greenish or reddish. Streak colorless. Colorless in section.

OCCUR. Found in metamorphic rocks most commonly in limestone where modified by contact metamorphism. Often associated with diopside, garnet, titanite, apatite, zircon, etc. Wernerite is the common scapolite.

DIAG. Distinguished from meionite by lower relief and weaker birefringence, from other scapolites by higher relief and stronger birefringence; distinguished from feldspars, cordierite and zoisite by stronger birefringence, uniaxial character, and cleavages; from quartz by stronger birefringence, negative sign, and cleavages; from prehnite and colorless micas by the uniaxial character; from andalusite by the uniaxial character and stronger birefringence.

## DIPYRE.

TETRAGONAL $c = 0.4424$ $Me_1Ma_2$ to $Me_1Ma_3$

PHYS. CHAR. Crystals long prismatic, vertically striated, with pyramidal terminations, often rounded, oval, etc. Also globular, massive. Cleavage distinct || 100 and 010. H. = 6. G. = 2.62-2.65. Fuses easily with little intumescence. Only slightly decomposed by acids.

OPT. PROP. Uniaxial and negative. Refringence and birefringence moderate, both decrease with increase in the proportion of marialite present.

$$n_g = 1.562 \text{ to } 1.5545$$
$$n_p = 1.546 \text{ to } 1.5417$$
$$n_g - n_p = 0.016 \text{ to } 0.0128$$

Colorless, milky, greenish, gray, violet, black. Distinct color is always due to inclusions or alterations. Colorless in section.

INCL. Dipyre usually has abundant inclusions which vary somewhat with the nature of the occurrence. In limestones colorless dipyre often contains inclusions of calcite; in black limestones the carbonaceous matter is often found exclusively as inclusions in dipyre if that mineral be present. The dipyre may also contain grains of quartz and scales of mica; in other cases inclusions of feldspar, amphibole, garnet, etc. In mica schists dipyre often contains many inclusions of mica, tourmaline, rutile, actinolite, etc. Sometimes these inclusions are oriented parallel with the vertical axis of the dipyre. In siliceous contact rocks (hornstone, etc.) dipyre contains inclusions of mica, pyroxene, tourmaline, etc. These are usually without orientation and thus produce a poikilitic texture. Sometimes they are more abundant than the dipyre which encloses them.

ALTER. The alteration products of dipyre are numerous, including mica (probably damourite), colorless or very pale green clinochlore (called leuchtenbergite), calcite, quartz, chabazite, stilbite, and sometimes a colloidal material. It is also sometimes metamorphosed to a mixture of forsterite and spinel.

OCCUR. Dipyre is found in various crystalline schists, in many rocks produced by contact metamorphism, and in igneous rocks modified by endomorphism.

DIAG. Distinguished from other scapolites (except marialite) by weaker birefringence and lower relief, from quartz by stronger birefringence, optic sign, and cleavages. See also wernerite.

## MARIALITE.

TETRAGONAL $c = 0.4417$ $Me_1Ma_4$ to $Me_0Ma_1$

PHYS. CHAR. Similar to dipyre in physical characters, but G. = 2.57, and nearly insoluble in acids.

OPT. PROP. Uniaxial and negative. Refringence and birefringence close to those of quartz.

$$n_g = < 1.554 \quad n_p = < 1.542$$

$$n_g - n_p = 0.010 \text{ about}$$

INCL. and ALTER. Similar to dipyre.

OCCUR. Found in volcanic rocks in Italy. Rare.

DIAG. Distinguished from other scapolites by weaker birefringence and lower relief, from quartz by optic sign and cleavages.

## SCHEELITE.

TETRAGONAL $c = 1.536$ $CaWO_4$

COMP. Molybdenum sometimes replaces considerable tungsten.

PHYS. CHAR. Crystals pyramidal, or tabular || 001. Also reniform, granular massive. Twinning on 100 of both contact and penetration types. Cleavage distinct || 111, indistinct || 101. H. = 4.5-5. G. = 5.9-6.1. Fusible at 5. Decomposed by HCl leaving a yellow residue.

OPT. PROP. Uniaxial and positive. Refringence high.

$$n_g = 1.935 \quad n_p = 1.919$$

$$n_g - n_p = 0.016$$

Color white, pale yellow, brownish, greenish, reddish. Streak white.

ALTER. Alteration to wolframite is frequent.

Occur. Found in crystalline rocks and pegmatite veins with cassiterite, topaz, fluorite, molybdenite, wolframite; also with gold ores.

**Stolzite** ($PbWO_4$) is isomorphous with scheelite, with $c = 1.567$. Crystals pyramidal; aggregated. Cleavage imperfect || 001, in traces || 111. H. = 2.5-3. G. = 7.87-8.13. Fusible with decrepitation at 2. Decomposed by $HNO_3$, leaving a yellow residue. Uniaxial and negative; $n_g = 2.2685$, $n_p = 2.182$; $n_g - n_p = 0.0865$. Color green, yellowish gray, brown, red. Streak colorless. Found in veins. Rare.

**Wulfenite** ($PbMoO_4$) is isomorphous with scheelite, with $c = 1.577$. Crystals varied in aspect, often tabular || 001, also prismatic or pyramidal. Massive, coarse or fine granular. Cleavage distinct || 111, indistinct || 001 and 113. H. = 2.5-3. G. = 6.7-7. Fusible below 2 with decrepitation. Decomposed by HCl. Uniaxial and negative; $n_g = 2.402$, $n_p = 2.304$; $n_g - n_p = 0.098$. Color wax yellow, orange yellow; also green, gray, nearly colorless, brown, bright red. Streak white. Found in veins with lead ores.

Diag. Scheelite differs from stolzite and wulfenite in sign and in much weaker birefringence.

**SCOLECITE,** see zeolite group.

## SCORODITE.

Orthorhombic $a : b : c :: 0.866 : 1 : 0.954$ $FeAsO_4 + 2H_2O$

Phys. Char. Crystals pyramidal, prismatic, or tabular || 100; aggregated; earthy. Cleavage imperfect || 120, in traces || 100 and 010. H. = 3.5-4. G. = 3.1-3.3. Easily fusible with blue flame. Soluble in HCl.

Opt. Prop. The optic plane is parallel to 100; the acute bisectrix Z is normal to 001. Optic angle large; dispersion $\rho > v$ very marked.

$$(+)\ 2E = 115^\circ\ 43'$$
$$n = 1.84$$

Color leek green to liver brown. Streak white. Pleochroic in thick sections with Z colorless to pink, X bluish green.

Occur. Found with arsenopyrite, enargite, limonite, pyrite, pharmacosiderite, etc., in limestone, or in cavities, or in veins; also formed about geysers.

## SELLAITE.

Tetragonal $c = 0.66$ $MgF_2$

Phys. Char. Crystals usually prismatic; fibrous. Cleavage perfect || 100 and 110. H. = 5. G. = 2.9-3.1. Fusible with intumescence. Soluble in pure $H_2SO_4$.

Opt. Prop. Uniaxial and positive. Refringence the lowest known among minerals, except ice and villiaumite. Colorless.

$$n_g = 1.3897 \quad n_p = 1.3780$$
$$n_g - n_p = 0.0117$$

Occur. Found in anhydrite or sulphur; also with fluorite Very rare.

Diag. Differs from scapolite by its easy cleavages and its optic sign.

**SENARMONTITE**, see arsenolite.

## SEPIOLITE.

Monoclinic? Axial ratio unknown $H_8Mg_2Si_3O_{12}$

Phys. Char. Unknown in distinct crystals, although always crystalline. Occurs in earthy to porous compact masses or lamellar. Cleavage perfect || 001, giving flexible laminæ; parting apparently || 010. H. = 2.-2.5. G. = 2. Dry porous masses float on water. Often adheres to the tongue on account of a tendency to absorb hygroscopic water; also may absorb oily substances, and is therefore used for cleaning purposes. In the closed tube promptly gives hygroscopic water, but does not decompose and yield its water of constitution except at red heat. It then gives a burnt smell, and is transformed to a white mass with H. = 6. Before the blowpipe usually blackens, then turns white, and fuses at about 6. Gelatinizes with HCl.

Opt. Prop. The negative acute bisectrix is perpendicular or nearly perpendicular to the lamellar cleavage 001. The angle of the optic axes is variable and may even be 0° on account of superposition of laminæ. The optic plane is parallel to 010.

$$(-)\ 2E = 112^\circ \quad 2V = 74^\circ \pm$$

$n_g > 1.549$ (index of balsam) $n_m < 1.549$ (index of balsam)

Color white, pink, greenish yellow. More transparent after immersion in a liquid. Colorless in thin section, but sometimes colored and pleochroic in thick laminæ with Z = Y = golden yellow, X = colorless to very pale yellow.

Incl. Sepiolite often has abundant inclusions; they are sometimes largely composed of calcite or dolomite, with or without silica. In Morocco the mineral contains a little potassium and magnesium sulphate.

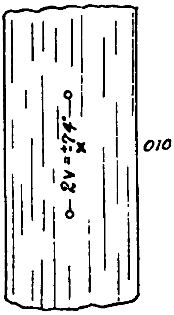

Figure 190. Optical orientation of sepiolite.

Occur. Sepiolite is found in lake deposits formed at the same time as gypsum and halite, according to Munier-Chalmas. Also found in thin layers in serpentine.

Diag. The variety *meerschaum* has a characteristic texture. Other varieties are usually to be distinguished from fine lamellar kaolinite and sericite only by abundance of magnesia and absence of alumina.

## SERENDIBITE.

Monoclinic or Triclinic $(Mg,Ca,Fe)_{10}B_2Al_{10}Si_6O_{46}$

Phys. Char. Crystals six-sided plates; granular. Twinning polysynthetic like plagioclase. Cleavage absent. H. = 7.±. G. = 3.42. Infusible. Insoluble.

Opt. Prop. Sections normal to the twinning plane with symmetrical extinction angles of 35°-40° are nearly normal to the acute bisectrix Z. Refringence high. Birefringence weak.

$$(+)\ 2V = \text{large}$$
$$n = 1.7 \pm$$

Color blue, light azure to dark indigo. In thin section strongly pleochroic with Z azure blue; Y, X pale yellowish green to colorless; in other cases the colors range from indigo blue to brownish yellow.

Occur. Found with diopside and green spinel between granulite and crystalline limestone. Very rare.

### Serpentine Group.

The minerals of the serpentine group are basic magnesian silicates, with iron or nickel in some cases. They are usually produced by alteration from ferromagnesian silicates, especially olivine. Usually massive, either foliated or finely fibrous. They are often colloidal and impure, and both their crystal system and composition are subject to revision. The minerals which are here included in this group are as follows:—

| | | |
|---|---|---|
| Antigorite | Orthorhombic (Pseudocubic) | $H_4Mg_3Si_2O_3$ |
| Chrysotile | Orthorhombic | $H_4Mg_3Si_2O_9$ |
| Bowlingite | Orthorhombic | Ferriferous antigorite |
| Xylotile | Orthorhombic | Ferriferous chrysotile |
| Deweylite | ? | $H_{12}Mg_4Si_3O_{16}$ |
| Genthite | ? | Nickeliferous deweylite |

## ANTIGORITE.

Orth. (Pseudocubic) Axial ratio unknown $H_4Mg_3Si_2O_3$

Phys. Char. Crystal form rare, simulating a cube modified by an octahedron. Complex twinning produces the pseudosymmetry. Usually in lamellar aggregates. Cleavage perfect || 100, easy || 010, and 001 in some cases. Parting rare || 111. H. = 3.-4. G. = 2.55-2.58. Difficultly fusible. Decomposed by HCl or $H_2SO_4$.

Opt. Prop. The plane of the optic axes is parallel to 010; the negative acute bisectrix is normal to 100, that is, the perfect cleavage. The elongation of the lamellæ is always positive. The optic angle is large, but superposition of lamellæ is almost con-

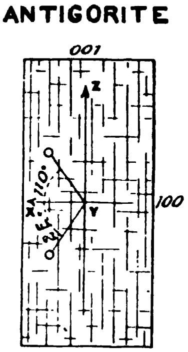

Figure 191.
Optical orientation of antigorite.

stant, always reducing the angle, often till it is nearly zero. Dispersion $\rho > v$ weak.

$$(-)2E = 110^\circ \pm$$
$$n_m = 1.570$$
$$n_g - n_p = \text{less than } 0.009$$

Color green of various shades, grayish, yellow, rarely white. Pale greenish to colorless in thin section. Pleochroic only in very thick sections; then:—

Z = pale green
Y = X = pale greenish yellow

Occur. Found commonly in peridotites and serpentine rocks resulting from their alteration; found also in other igneous and metamorphic rocks as an alteration product of olivine, pyroxene, amphibole, and other ferromagnesian silicates.

**Bastite** is a lamellar variety of antigorite; it is always pseudomorphous after pyroxene, usually orthorhombic, sometimes monoclinic (diopside). It forms by regular gradual development, so that one crystal of bronzite is replaced by one crystal of bastite in which the easy cleavage 100 corresponds to the (cleavage or) parting 010 of the rhombic pyroxene.

Diag. Distinguished from chrysotile by position and sign of the acute bisectrix, weaker birefringence, and larger optic angle; also by lamellar structure rather than fibrous.

## CHRYSOTILE.

Orthorhombic Axial ratio unknown $H_4Mg_3Si_2O_9$

Phys. Char. Usually in fibrous masses without crystal form. Fibers usually separable and flexible. Prismatic cleavage making an angle of 130° rarely visible. Color green, golden yellow, greenish gray. H. = 2.-3. G. = 2.36-2.52. Density variable on account of porosity. Fusible at 6. Decomposed by acids leaving skeleton fibers of silica.

Opt. Prop. The plane of the optic axes is parallel to 010 and the positive acute bisectrix is parallel to the elongation of the fibers, that is parallel to *c*. The obtuse bisectrix is normal to 100. The optic angle is small and superposition may make it apparently zero. The same cause often reduces the apparent strength of the double refraction.

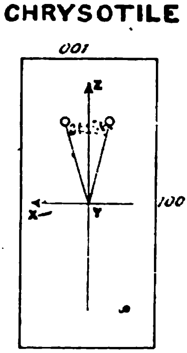

Figure 192.
Optical orientation of chrysotile.

$$(+)\ 2V = 30^\circ \text{ to } 35^\circ$$
$$n = 1.54 \pm$$
$$n_g - n_p = 0.013$$

Color green, golden yellow, greenish, gray. Luster often silky. In thin section pale greenish or yellow to colorless, but in thick sections pleochroism distinct with

Z = green or yellow
Y = X = greenish yellow to colorless

Occur. Found commonly associated with antigorite in serpentine rocks; also in veins in such rocks; less commonly as a decomposition product of ferromagnesian minerals in various other rocks.

Diag. Distinguished from antigorite by position and sign of the acute bisectrix, the small optic angle, and the somewhat stronger birefringence; also by fibrous structure, rather than lamellar. Distinguished from fibrous amphiboles by much weaker birefringence, lower relief and parallel extinction.

## BOWLINGITE.

| | | |
|---|---|---|
| Orthorhombic? | Axial ratio unknown | Hydrous silicate of iron, magnesium, aluminum. |

Comp. Bowlingite seems to be a ferriferous antigorite, or, more exactly, a hydrated silicate of iron and magnesium with a little aluminum. More or less of the iron is oxidized to the ferric state in the yellow and brown varieties.

Phys. Char. Not known in crystal form except as pseudomorphs after olivine. Also fibrous or fibrolamellar. Cleavage perfect || 100; more rarely also transversal cleavage. G. = 2.29-2.3. Easily soluble in HCl.

Opt. Prop. The plane of the optic axes is parallel to 010; the negative acute bisectrix is normal to 100, that is, the easy cleavage. The optic angle is always small, often near zero. The refringence is less than that of olivine, and similar to that of antigorite, while the birefringence exceeds 0.025 in the dark yellow varieties.

$$(-)\ 2E = 35^\circ \text{ to } 40^\circ \text{ maximum}$$
$$n_g - n_p = > 0.025$$

Color green, yellow to reddish brown, depending upon the state of oxidation of the iron. In thin section pleochroism is always distinct, and very marked in the green varieties, as follows:—

| | | |
|---|---|---|
| Z = green | golden yellow | dark reddish yellow |
| Y = clear green | clear yellow | reddish yellow |
| X = greenish yellow | pale yellow | reddish yellow |

Alter. In the alteration of olivine to bowlingite the latter often orients itself upon the former, a single crystal of one changing to a single crystal of the other. In this case 100 of bowlingite coincides with 001 of the olivine, and the optic plane of the former is parallel to 010 of the latter. In other cases a crystal of olivine may be changed by progressive alteration to a fibrolamellar aggregate of bowlingite. Secondary magnetite often forms irregular inclusions in bowlingite.

Occur. Found as an alteration product of ferriferous olivine in basic igneous rocks. Common in rocks from Lake Superior region.

**Iddingsite** is described as a hydrous silicate of iron, magnesium and calcium, which is perhaps the same as bowlingite. The two are alike in physical characters, alike in optical characters, and alike in their common origin from olivine, and even in the mode of alteration producing them. Iddingsite seems to differ somewhat in specific gravity (G. = 2.84), and in the presence of calcium. In all other characters, including mode of occurrence, it resembles bowlingite very closely.

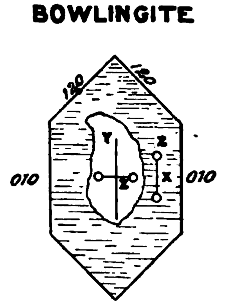

Figure 193. Relative orientation of olivine and bowlingite, the former altering to the latter.

Diag. Distinguished from antigorite by color, pleochroism, and much stronger birefringence. Also by abundance of iron. Distinguished from goethite, which is another common alteration product of olivine in certain localities, by refringence, less than that of olivine, while goethite has refringence higher than that of olivine. Further, goethite dissolves in cold dilute HCl much more rapidly than bowlingite.

## XYLOTILE.

| | | |
|---|---|---|
| Orthorhombic? | Axial ratio unknown | Hydrous silicate of iron and magnesium. |

Comp. Xylotile may be considered a ferriferous chrysotile, or a hydrated silicate of iron and magnesium in which more or less of the iron may be oxidized to the ferric state.

Phys. Char. Similar to bowlingite. G. = 2.56 (green variety) to 2.4 (brown variety). Fusible. Decomposed by warm HCl leaving a skeleton of silica.

Opt. Prop. The positive acute bisectrix is parallel with the elongation of the fibers, as in chrysotile. The optic angle is small. The birefringence is considerable.

$$(+)\ 2E = 20^\circ \text{ about}$$
$$n_g - n_p = 0.026 \text{ about}$$

Color green or brown. In thin section the pleochroism is intense, with Z = very dark golden yellow; Y = X = pale yellowish.

Occur. Found sparingly in some serpentine rocks and in crystalline limestone. Rare.

**Thermophyllite** is a hydrous silicate of magnesium, aluminum and sodium; cleavage laminæ are flexible, inelastic; H. = 2.5. G. = 2.6. Fusible at 6. Slowly attacked by $H_2SO_4$. Negative acute bisectrix normal to cleavage; $2E = 20^\circ - 22^\circ$; $n_g - n_p = 0.03 \pm$. Silver white, yellowish, etc. Luster pearly. Found in serpentine.

Diag. Xylotile is distinguished from chrysotile by color, intense pleochroism, and rather strong birefringence. Distinguished from bowlingite by the position of the acute bisectrix with respect to the cleavage and fibers, and by the optic sign; also by the fibrous structure rather than the lamellar or fibrolamellar.

## DEWEYLITE.

ORTHORHOMBIC? Axial ratio unknown $H_{12}Mg_4Si_3O_{16}$

Phys. Char. Found in translucent masses having the appearance of gum. White, yellow, reddish, or green. H. = 2.-3.5. G. = 2.-2.3. Gives much water in the closed tube. Decrepitates when heated, becomes opaque, and fuses at 6. Slowly attacked by HCl.

Opt. Prop. The angle of the optic axes is quite small. The sign is positive. The mineral is always finely fibrous like chalcedony; it is sometimes perfectly spherulitic. The elongation of the fibers is positive.

$$(+)\ 2E = \text{small}$$
$$n = < 1.55$$

Color white, yellow, reddish, green.

Occur. Found in veins in serpentine rocks and in crystalline limestones. Rare.

Diag. The microstructure is characteristic of deweylite as compared with the other minerals of the group. Distinguished from chalcedony by the sign of the bisectrix and the sign of the elongation.

## GENTHITE.

ORTHORHOMBIC? Axial ratio unknown $H_{18}(Ni,Mg)_8Si_7O_{31}$?

Comp. Many analyses have been made, but the formula is still quite uncertain. Genthite may be simply a nickeliferous deweylite.

Phys. Char. Commonly found in mammillary or stalactitic forms with greasy luster or feel. Sometimes earthy and rough. H. = 1.-3. G. = 2.27-2.87, varying with the amount of nickel present. Infusible. Decomposed by HCl without gelatinization.

Opt. Prop. The angle of the optic axes is very small. The sign is positive. The mineral is often finely fibrous like chalcedony and deweylite; sometimes spherulitic. The elongation of the fibers is positive. In other cases it is cryptocrystalline or amorphous. In garnierite, $n = 1.59$.

Color dark green, pale green, yellow; in thin section bright green, rarely yellowish.

Occur. Genthite, or the closely related if not identical minerals **garnierite** and **nouméite**, forms the chief ore of nickel in New Caledonia. Common associates are chromite, other serpentine minerals, olivine, steatite, etc. Also found with similar associates in Pa., Ore., N. C., etc.

**Nepouite** is a hydrous nickel magnesium silicate $[H_4(Ni,Mg)_3Si_2O_9]$ perhaps related to genthite; it has two cleavages; G. = 2.47-3.24. Refringence and birefringence increase with the nickel content from 1.56 and less than 0.03 respectively to 1.62-1.63 and 0.038. The optic sign is negative; the optic plane nearly parallel to the inferior cleavage, and an optic axis is nearly normal to the lamination. Color greenish, X green, Z greenish yellow. Found in New Caledonia.

Diag. Genthite is distinguished from other members of the group by marked green color, chalcedonic to amorphous texture, and presence of nickel.

**SERPIERITE**, see brochantite. **SEYBERTITE**, see clintonite group. **SIDERITE**, see calcite group.

## SILLIMANITE.

Orthorhombic $a:b:c::0.6873:1:?$ $Al_2SiO_5$

Phys. Char. Crystals prismatic, much elongated without terminal faces. Prismatic striations. Sometimes even fibrous; then often compactly interlaced. Cleavage very perfect || 100, showing distinctly in sections when the crystals are not too small. H. = 6.-7. G. = 3.17-3.24. Infusible. Insoluble. Colored blue by heating after moistening with cobalt nitrate.

Opt. Prop. The plane of the optic axes is parallel to 100, that is, the plane of the cleavage. The positive acute bisectrix is parallel with $c$. The elongation is therefore always positive. The relief is marked and the birefringence strong. The optic angle is small and somewhat variable. The dispersion of the optic axes is strong, with $\rho > v$.

| | Ceylon | Morlaix, France | Saybrook |
|---|---|---|---|
| (+) $2V =$ | 31° | 26° | 25° |
| $n_g =$ | 1.6766 | 1.680 | 1.6818 |
| $n_m =$ | 1.6577 | 1.661 | 1.6612 |
| $n_p =$ | 1.6562 | 1.659 | 1.6603 |
| $n_g - n_p =$ | 0.0204 | 0.021 | 0.0215 |

The variations in the indices of refraction and the optic angle may be due to the presence of pigments. Thus, Hlawatsch has found in dark brown sillimanite from Saybrook $n_g = 1.6773$ and $n_p = 1.6549$, while in the pale brown variety from the same place $n_g = 1.6837$ and $n_p = 1.6612$.

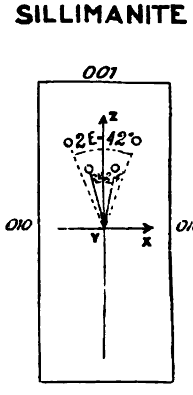
SILLIMANITE

Figure 194.
Optical orientation of sillimanite.

Colorless, yellowish, greenish or colored brown by scales of biotite lying between the acicular sillimanite crystals. Pleochroism is not perceptible in thin sections. In thick sections a pleochroism is to be observed, which is often, if not always, due to the fine inclusions of biotite, as follows:—

| | |
|---|---|
| X = pale brownish | pale to brownish yellow |
| Y = brown | pale to grayish green |
| Z = dark brown | violet blue |

INCL. Sillimanite often contains inclusions of spinel or biotite or glass. The spinel may be an alteration product in some cases—either from sillimanite or from the accompanying mica.

OCCUR. Sillimanite occurs most abundantly in crystalline schists, gneisses and related rocks; it is found also in eclogite, and some other metamorphic rocks. In igneous rocks it occurs only as a result of absorption of foreign materials. Also produced by contact metamorphism near granite.

DIAG. Distinguished from andalusite and zoisite by the positive character of the elongation, the strong birefringence, and the position of the optic plane with reference to the cleavage. Distinguished from scapolite minerals by the cleavage and the biaxial character. Interlacing needles are characteristic of the variety *fibrolite*.

**SILVER,** see gold group. **SMALTITE,** see pyrite group.

**SMITHITE.**

MONOCLINIC $a:b:c::2.22:1:1.957$ $AgAsS_2$

$$\beta = 78° 48'$$

PHYS. CHAR. Crystals apparently hexagonal, tabular. Cleavage perfect || 100. H. = 1.5-2. G. = 4.88.

OPT. PROP. The optic plane is parallel to 010; the acute bisectrix X makes an angle of about 6° with a normal to 100 in the obtuse angle $\beta$. Refringence extremely high; birefringence strong.

$$(-)\ 2V = 65° \pm$$
$$n = 3.27 \pm$$

Color and streak scarlet vermilion, altering to orange red. Pleochroism weak even in thick plates.

OCCUR. Found in dolomite. Very rare.

**Hutchinsonite** is related chemically to smithite, but contains more elements $[Pb,(Tl,Ag)_2As_4S_8]$. It is orthorhombic with $a:b:c::1.634:1:0.755$. Crystals prismatic; cleavage good || 100. H. = 1.5-2. G. = 4.6. Optic plane parallel to 100; acute bisectrix X normal to 010. Refringence extremely high; $n_g = 3.188$, $n_m = 3.176$, $n_p = 3.078$; $n_g - n_p = 0.110$. Color and streak scarlet vermilion to deep cherry red. Pleochroism weak. Found with smithite. Very rare.

**SMITHSONITE,** see calcite group.

**Sodalite Group.**

The sodalite group includes four minerals which are silicates of sodium and aluminum, and contain in addition either chlorine, sulphur, or the sulphuric acid radical. They crystallize in the isometric system and may be isomorphous with the garnets. Crystals are often dodecahedral, but a massive granular condition is common. They are sometimes twinned on the spinel law (twinning plane 111). Dodecahedral cleavage is present, but not perfect. H. = 5.-6. G. = 2.1-2.5.

The minerals of this group are all easily attacked by acids, even acetic acid, with the production of gelatinous silica; therefore in nature they alter very readily. They fuse at 3. to 5. with intumescence to a colorless glass.

The minerals of the group are as follows:—

| | |
|---|---|
| Sodalite | $(3NaAlSiO_4 + NaCl$ or$)$ $Na_4(AlCl)Al_2(SiO_4)_3$ |
| Noselite | $(4NaAlSiO_4 + Na_2SO_4$ or$)$ $Na_4(NaSO_4 \cdot Al)Al_2(SiO_4)_3$ |
| Haüynite | $[2(Na_2,Ca)Al_2Si_2O_8 + (Na_2,Ca)SO_4$ or$]$ $(Na_2,Ca)_2(NaSO_4 \cdot Al)Al_2(SiO_4)_3$ |
| Lazurite | $(Na_2,Ca)_2[(NaS_3,NaSO_4,Cl)Al]Al_2(SiO_4)_3$ |

## SODALITE.

ISOMETRIC $Na_4(AlCl)Al_2(SiO_4)_3$

PHYS. CHAR. Crystals are usually dodecahedrons, but more commonly without crystal faces in embedded grains; also in concentric nodules. Is an alteration product from eleolite. Cleavage dodecahedral 110 indistinct, generally invisible in thin section. Twinning with twinning plane 111 not common. Fracture conchoidal. H. = 5.-6. G. = 2.14-2.4. Fusible at 3.5-4. to a colorless glass. In boiling water the powdered mineral yields NaCl. Soluble even in acetic acid, with separation of gelatinous silica.

OPT. PROP. Isotropic; sometimes weakly birefringent about inclusions. The index of refraction varies slightly with variations in the precise composition.

$$n = 1.4827 - 1.4868$$

Colorless, gray, yellow, blue, greenish, pale red. In thin section colorless, yellow, blue, pink.

ALTER. Alteration is common. The mineral may change to a fibrous mass of zeolites (natrolite, hydronephelite, etc.), or to a lamellar aggregate of a micaceous mineral (muscovite, hydrargillite, diaspore). Also it may change to cancrinite, to garnet, or to a fibrous amorphous substance of a pink or a brown color. The alteration of the mineral is often accompanied by the formation of calcite and limonite.

OCCUR. Found only in eruptive rocks rich in soda, or, rarely, in limestones, etc. modified by such rocks. It often accompanies nepheline in phonolites and theralites.

DIAG. The minerals of the sodalite group are distinguished from all other monorefringent substances (except volcanic glass, fluorite, leucite and analcite) by their very low refractive index. They are distinguished from these substances by their form, cleavage, absence of twinning structure, and chemical reactions. The minerals of the sodalite group are distinguished one from another by the following test: the mineral is covered on a glass slide by a little nitric acid which is allowed to evaporate slowly; in a short time crystals of sodium chloride may form (sodalite), or crystals of gypsum may form (haüynite); if neither of these crystals form before, but both form after the addition of a little $CaCl_2$ we have noselite. Lazurite is distinguished from the other three minerals of the group by the evolution of hydrogen sulphide, when thus attacked, which will blacken silver filings. It is further distinguished by its mode of occurrence, which is as a contact mineral in limestone.

## NOSELITE.

ISOMETRIC $Na_4(Al \cdot NaSO_4)Al_2(SiO_4)_3$

PHYS. CHAR. Similar to sodalite. H. = 5.5. G. = 2.25-2.4. Fusible at 5. to a white glass. Easily soluble in acids with separation of gelatinous silica.

OPT. PROP. Nearly always monorefringent, but optic anomalies occur, which seem to have some connection with the presence of inclusions.

$$n = 1.4815 - 1.4965$$

Colorless, white, gray, lavender blue, on account of alterations and inclusions, yellowish, brown, red, or black. In thin section the blue color is sometimes very bright; it is usually irregularly distributed in the midst of colorless or paler colored portions.

INCL. Microscopic inclusions are often abundant. They may be gaseous, liquid, vitreous, or crystalline. They are sometimes irregularly arranged in zones or along certain axes. The crystalline inclusions may be magnetite or ilmenite, often with definite orientation, and sometimes extremely abundant.

ATLER. Alteration products are similar to those of sodalite. The ferriferous inclusions may also alter to limonite, and thus color the mineral in mass a yellow or brown.

OCCUR. Found exclusively in phonolites, certain leucite rocks. and similar igneous types.

DIAG. See sodalite.

## HAUYNITE.

ISOMETRIC $(Na_2,Ca)_2(Al \cdot NaSO_4)Al_2(SiO_4)_3$

PHYS. CHAR. Similar to sodalite. H. = 5.5-6. G. = 2.4-2.5. Fusible at 4.5 to a white glass. Easily soluble in acids with separation of gelatinous silica.

OPT. PROP. Optic anomalies rare; they seem to have some connection with the presence of inclusions. The index of refraction varies directly with the percentage of CaO.

$$n = 1.4930 - 1.5090$$

Usually blue. Also green, or, by alteration, yellow to red. Inclusions may produce a gray to black color. In thin section the blue coloration is sometimes very bright; it is usually irregularly distributed.

INCL. and ALTER. Similar to noselite.

OCCUR. Found exclusively in phonolites, theralites, and related igneous rocks usually associated with nepheline and leucite.

DIAG. See sodalite.

### LAZURITE.

ISOMETRIC $(Na_2,Ca)_2[Al(NaS_3,NaSO_4,Cl)]Al_2(SiO_4)_3$

PHYS. CHAR. Similar to sodalite. In dodecahedrons or cubes, or in compact masses. H. = 5.-5.5. G. = 2.38-2.45. Fusible at 3 to a white glass. Easily soluble in acids with separation of gelatinous silica and evolution of hydrogen sulphide.

OPT. PROP. Optic anomalies rare; usually monorefringent. Index of refraction very near that of haüynite.

Color blue both in mass and in thin section.

OCCUR. Found exclusively in crystalline limestones, apparently always due to contact metamorphism.

DIAG. See sodalite.

### SODA NITER.

RHOMBOHEDRAL $c = 0.828$ $NaNO_3$

PHYS. CHAR. Crystals rhombohedral, rare; massive, encrusting. Cleavage perfect || $10\bar{1}1$. H. = 1.5-2. G. = 2.24-2.29. Deflagrates on charcoal with yellow flame. Deliquescent. Soluble in $H_2O$. Taste cooling.

OPT. PROP. Uniaxial and negative. Birefringence extremely strong.

$$n_g = 1.5874 \quad n_p = 1.3361$$
$$n_g - n_p = 0.2513$$

Color white, or colored yellow, brown, or gray by impurities. Luster vitreous. Colorless in section.

OCCUR. Found with gypsum, halite, glauberite, etc., as a surface formation in arid regions.

### SPANGOLITE.

RHOMBOHEDRAL $c = 2.011$ $Cu_6(OH)_{12}(AlCl)SO_4 + 3H_2O$

PHYS. CHAR. Crystals tabular || 0001 to short prismatic, horizontally striated. Cleavage perfect || 0001. H. = 2.-3. G. = 3.14. Fusible at 3 with green flame. Soluble in dilute acids.

OPT. PROP. Uniaxial and negative. Refringence high; birefringence strong.

$$n_g = 1.694 \quad n_p = 1.641$$
$$n_g - n_p = 0.053$$

Color dark green. Luster vitreous. Pleochroism weak with Z green and X bluish green.

OCCUR. Found with cuprite and azurite. Very rare.

**SPESSARTITE,** see garnet group.

### SPHALERITE.

ISOMETRIC $ZnS$

PHYS. CHAR. Crystals tetrahedral, but often much modified and complex. Commonly massive cleavable. Also granular, foliated, fibrous; rarely pulverulent. Twinning on 111 simple or multiple. Cleavage perfect || 110. H. = 3.5-4. G. = 3.9-4.1. Difficultly fusible. Soluble in HCl with evolution of $H_2S$.

Opt. Prop. Isotropic; rarely anisotropic, probably on account of strain, since anisotropic areas are easily produced by pressure with a pin point on a section. Refringence extremely high, $n = 2.3692$. Color brown, black, yellow; rarely green, red, white, colorless. Streak paler. In thin section colored varieties often show zonal distribution of the color. Luster resinous.

Alter. Sphalerite alters by weathering to goslarite, smithsonite, calamine, and sometimes limonite.

Occur. Sphalerite is found abundantly in veins, less commonly disseminated in sedimentary rocks. It is quite constantly associated with galena; also often with chalcopyrite, tetrahedrite, calcite, dolomite, siderite, fluorite, barite.

### Spinel Group.

The minerals of the spinel group are aluminates, ferrates, chromates, etc. of magnesium, iron, zinc, or manganese. The minerals of the group crystallize in the isometric system; "optic anomalies" are unknown in them. They occur commonly in rounded grains without distinct cleavage. Crystals are usually octahedrons, less commonly dodecahedrons, or modified forms of these types. Twinning on 111 is not rare, that is, according to the "spinel law." H. = 5.5-8. G. = 3.5-5.5. All colors are found. The more important species of the group are:

| | |
|---|---|
| Spinel | $MgAl_2O_4$ |
| Picotite | $(Mg,Fe)(Al,Fe,Cr)_2O_4$ |
| Gahnite | $ZnAl_2O_4$ |
| Hercynite | $FeAl_2O_4$ |
| Chromite | $FeCr_2O_4$ |
| Magnetite | $FeFe_2O_4$ |
| Franklinite | $(Fe,Zn,Mn)(Fe,Mn)_2O_4$ |
| Jacobsite | $(Mn,Mg)(Fe,Mn)_2O_4$ |
| Magnesioferrite | $MgFe_2O_4$ |

### SPINEL.

Isometric $MgAl_2O_4$

Phys. Char. Crystals octahedrons; sometimes modified. Also in grains. Twinning on 111 sometimes polysynthetic. Cleavage imperfect || 111. Fracture conchoidal. H. = 8. G. = 3.5-3.7; 4.-4.1 in *picotite*. Infusible. Slowly soluble in $H_2SO_4$.

Opt. Prop. Strictly isotropic in thin section. Index of refraction high, varying with the composition and depth of color.

$$n = 1.71\text{-}1.73$$

Color red, blue, green, yellow, brown, black, rarely nearly white. In thin section lighter shades. Not pleochroic. The variety *pleonaste,* which contains iron, is usually green, and *picotite,* which contains iron and chromium, is dark yellowish brown to greenish brown.

Alter. Usually unaltered even in much disintegrated rocks. It has been found changed to muscovite, to steatite, to serpentine, and to hydrotalcite.

Occur. Spinel proper, which is the pure magnesian variety, is red, blue, pale green, or colorless, and occurs chiefly in crystalline limestones and schists. **Pleonaste** has been found associated with magnetite in igneous rocks, but is common in crystalline limestones and schists; also in zone of contact metamorphism. **Picotite** is related to chromite and occurs in basic igneous rocks, and in derived rocks; it is also known in crystalline schists.

Diag. Distinguished from garnet by its octahedral form and by the absence of silica. Picotite has lighter color, lower density, and greater hardness than chromite. Pleonaste resembles hercynite but has lower density and abundant magnesia.

## GAHNITE.

Isometric $ZnAl_2O_4$

Phys. Char. Crystals octahedral; less commonly dodecahedral or modified cubes. Twinning plane 111. Cleavage indistinct || 111. Fracture conchoidal. H. = 7.5-8. G. = 4.-4.6. Infusible. Slowly soluble in $H_2SO_4$.

Opt. Prop. Isotropic and not pleochroic. Index of refraction high. $n = 1.765$

Color green to black; rarely yellowish or grayish brown. Streak grayish. In thin section lighter shades.

Occur. Rare; found in crystalline schists and in veins.

Diag. Distinguished from garnet by its usual octahedral form and by the absence of silica; only distinguishable from other green and brown spinels by associated zinc minerals and by chemical composition.

## HERCYNITE.

Isometric $FeAl_2O_4$

Phys. Char. Found in fine granular masses. H. = 7.5-8. G. = 3.91-3.95. Infusible. Partly fusible with soda to olive green mass.

Opt. Prop. Isotropic in thin section. Index of refraction high.

$$n = 1.749$$

Color black. Streak green. In thin section green without pleochroism.

Occur. Rare; found especially in contact metamorphic rocks rich in alumina.

Diag. Distinguished from pleonaste by greater density and more abundant iron.

## CHROMITE.

Isometric $FeCr_2O_4$

Phys. Char. Crystals rare. Octahedrons, sometimes modified. Usually massive, granular. Cleavage unknown. Fracture uneven. H. = 5.5. G. = 4.32-4.57. Infusible except in reducing flame where it is fusible at 6, and becomes magnetic. Insoluble.

Opt. Prop. Isotropic. In thin section translucent to opaque. Index of refraction high.

$$n = 2.0695$$

Color black. Streak brown. Luster submetallic to metallic. In extremely thin flakes brown, reddish brown, yellowish red. Not pleochroic.

Occur. Found as a primary mineral in basic igneous rocks. and in derived rocks, such as serpentine. Also found in crystalline schists and in dolomite. It occurs, further, in some meteorites.

Diag. Closely resembles picotite, which has a lighter color, a lower specific gravity, and greater hardness. Distinguished from magnetite by absence of blue-black luster and of strong magnetism.

## MAGNETITE.

Isometric $FeFe_2O_4$

Comp. Magnetite varies in composition through rather wide limits; not only may the ferrous iron be replaced by more or less Mg, Mn, more rarely Ni, but the ferric iron may be replaced by more or less Al, Mn, or small amounts of Cr, V. Again, $TiO_2$ may be present in notable amount. Finally, the ratio between FeO and $Fe_2O_3$ is normally 1 : 1, but the $Fe_2O_3$ may increase till the ratio becomes 1 : 2, or 1 : 3, or even 1 : 4.

Phys. Char. Crystals commonly octahedrons; also dodecahedrons more or less modified; cubes quite rare. Also massive, laminated or granular. Twinning plane 111, sometimes in polysynthetic lamellæ. Cleavage indistinct; parting octahedral often well developed. Strongly

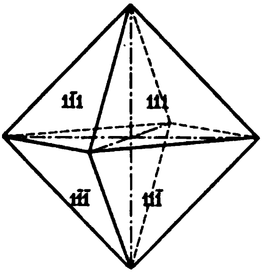

Figure 195.
Simple crystal form of magnetite.

magnetic; sometimes has polarity. H. = 5.5-6.5. G. = 5.17-5.18. Fusible at 6. Demagnetized by the oxidizing flame. Soluble in HCl.

OPT. PROP. Opaque in all artificial sections. Isotropic. Index of refraction high.

Color iron black. Streak black. Luster metallic to submetallic. In extremely thin flakes between cleavage lamellæ of mica it is translucent and pale brown to black. It is of a blue-black color in reflected light.

ALTER. Magnetite alters to hematite, limonite or siderite.

INCL. Apatite and zircon occur as inclusions in magnetite in some igneous rocks. By dissolving the enclosing magnetite ilmenite has been found within so oriented that the trigonal axes of the two minerals are parallel. In other cases rutile needles have been found lying parallel with the octahedral edges.

OCCUR. Magnetite is very widespread in its occurrence in igneous and metamorphic rocks. It is found sparingly in acid rocks, but quite abundantly in some basic types, even forming masses of commercial importance associated with basic igneous rocks. Similar masses are sometimes formed by metamorphism of deposits of limonite and hematite. It is one of the earliest minerals to solidify from magmas, associated in time with apatite and zircon, and commonly enclosed in the ferromagnesian silicates. Recrystallization of augite at high temperature results in paramorphs of hornblende and biotite with borders of magnetite; cleavage lines of the transformed pyroxene may be marked also by magnetite.

DIAG. Magnetite is distinguished from hematite and chromite by its blue-black color in reflected light. It is distinguished from graphite by its crystal form, hardness, and usually better metallic luster. It is distinguished from ilmenite by its crystal form, strong magnetism, and ready solubility in HCl. Ilmenite alters to leucoxene, but this may also develop from titaniferous magnetite.

## FRANKLINITE.

ISOMETRIC $(Fe.Zn,Mn)(Fe,Mn)_2O_4$

PHYS. CHAR. Crystals octahedral, often rounded; also granular. Parting octahedral. Slightly magnetic. H. = 5.5-6.5. G. = 5.07-5.22. Infusible. Reacts for Mn and Zn. Soluble in HCl.

OPT. PROP. Opaque in thin section. Index of refraction high.

Color iron black. Streak dark reddish brown or black. Luster metallic.

Occur. Franklinite occurs in calcite associated with zinc and manganese minerals at Franklin furnace, N. J., and elsewhere; rare. The variety **jacobsite** (Mn,Mg)(Fe,Mn)$_2$O$_4$, with G. = 4.75, blackish brown color and brilliant luster, is found in crystalline limestone in Sweden.

Diag. Only distinguished from magnetite by associated minerals, less magnetism, streak, and chemical tests for Mn and Zn.

## MAGNESIOFERRITE.

Isometric $MgFe_2O_4$

Phys. Char. Crystals simple and modified octahedrons. H. = 6.-6.5. G. = 4.57-4.68.

Opt. Prop. Opaque in thin section. Index of refraction high. Color and streak black. Luster metallic.

Occur. Found associated with crystals of hematite about fumaroles; rare.

Diag. Only distinguished from magnetite by chemical tests for Mg.

**SPODUMENE,** see pyroxene group.

## STAUROLITE.

Orth. $a:b:c::0.4723:1:0.6807$ $Fe(AlOH)(AlO)_4(SiO_4)_2$?

Phys. Char. Crystals short prisms with base and brachypinacoid. Anhedral forms rare. Cruciform twins common, the twinning plane either 032 resulting in nearly rectangular crosses, or 232 giving a cross with an angle of 60° 31′. Cleavage distinct || 010, in traces || 110. H. = 7.-7.5. G. = 3.65-3.75. Infusible. Slowly attacked by $H_2SO_4$. Insoluble in cold HF.

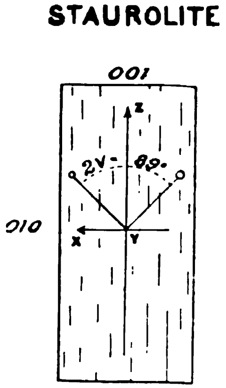

Figure 196.
Optical orientation of staurolite.

Opt. Prop. The plane of the optic axes is parallel to 100; the positive acute bisectrix is normal to 001. The refringence is high, but the birefringence is not strong. The angle of the optic axes varies from 88° 30′ to about 90°. The axial dispersion is weak with $\rho > v$. The angle of the optic axes decreases with increase of temperature.

$$(+)\ 2V = 88°\ 46'$$

$$n_g = 1.746 \quad n_m = 1.741 \quad n_p = 1.736$$

$$n_g - n_p = 0.010 \text{ to } 0.015$$

Color dark reddish brown to brownish black and yellowish brown.

Streak uncolored to gray. Luster subvitreous. Pleochroism is always visible in thin section, but the intensity is variable, and greater around inclusions. The absorption is Z>Y>X.

Z = golden yellow
Y = pale yellow
X = colorless

INCL. Staurolite very frequently contains abundant inclusions of quartz in anhedral forms; inclusions of rutile, tourmaline, garnet, etc. also occur. In the limestones it is sometimes filled with carbonaceous inclusions; these are rarely found regularly arranged, as in chiastolite.

ALTER. Staurolite alters to a green mica of rather large optic angle. It also changes to chlorite.

OCCUR. Staurolite occurs in crystalline schists, especially mica schists and phyllites. Its common associates are garnet, cyanite, andalusite, and sillimanite.

DIAG. In thin section staurolite is characterized by strong pleochroism in golden yellow tints with maximum absorption parallel with the positive elongation, together with parallel extinction and weak birefringence. The crystal forms and twins are also quite characteristic.

## STIBIOTANTALITE.

ORTHORHOMBIC $a:b:c::0.7995:1:0.8448$ $(SbO)_2(Ta,Nb)_2O_6$

PHYS. CHAR. Crystals of varied habit, often flattened || 100; sometimes hemihedral. Cleavage very perfect || 100, indistinct || 010. H. = 5.-5.5. G. = 6.-7.4, varying with varying percentage of Ta and Nb present. Fusible at 4. Insoluble, except in HF.

OPT. PROP. The optic plane is parallel to 100; the acute bisectrix Z is normal to 001. The refringence is extremely high; the dispersion $\rho < v$ is strong, increasing with increase of Nb.

| | $Ta_2O_5$ 39% | $Ta_2O_5$ 22.5% |
|---|---|---|
| (+) | $2V = 75° 5'$ | $2V = 73° 25'$ |
| | $n_g = 2.4568$ | $n_g = 2.4588$ |
| | $n_m = 2.4039$ | $n_m = 2.4190$ |
| | $n_p = 2.3742$ | $n_p = 2.3977$ |
| | $n_g - n_p = 0.0826$ | $n_g - n_p = 0.0611$ |

Color dark brown. Luster brilliant, resinous to adamantine. Resembles some sphalerite very closely.

OCCUR. Found in pegmatite with tourmaline, beryl, quartz, etc. Very rare.

**Columbite** [$Fe(Ta,Nb)_2O_6$] is isomorphous with stibiotantalite, with $a:b:c::0.8285:1:0.8897$; holohedral; crystals short prismatic, or tabular || 100; massive. Cleavage distinct || 100, indistinct || 010. H. = 6. G. = 5.3-7.3, varying with composition. Infusible. Nearly insoluble. Usually opaque, sometimes reddish brown and translucent. Color iron black to grayish or brownish black, often iridescent. Streak dark red to black. Luster often brilliant. Found chiefly in pegmatite, often with wolframite, beryl, feldspar, cassiterite, etc.

**STIBNITE.**

ORTHORHOMBIC $a:b:c::0.993:1:1.018$ $Sb_2S_3$

PHYS. CHAR. Crystals long prismatic, vertically striated, often in acicular radiating groups; massive, columnar, granular. Cleavage perfect || 010, imperfect || 100 and 110; gliding plane 001. H. = 2. G. = 4.52-4.62. Fusible at 1. Soluble in HCl.

OPT. PROP. Nearly opaque, but translucent to red and infra red rays; in such light the optic plane is parallel to 100, the negative acute bisectrix is normal to 001, the optic angle is small, the refringence extremely high, the birefringence extremely strong, and the dispersion extreme.

$$(-)\ 2V = 25^\circ\ 45'$$

$$n_g = 4.303 \quad n_m = 4.046 \quad n_p = 3.194$$

$$n_g - n_p = 1.109$$

Color and streak steel gray, subject to black tarnish. Luster metallic, often splendent.

ALTER. Oxidation of stibnite produces kermesite or valentinite.

OCCUR. Found commonly in veins with sphalerite, galena, cinnabar, barite, quartz, etc. Also found disseminated in limestone.

**STILBITE,** see zeolite group.

**STOKESITE.**

ORTHORHOMBIC $a:b:c::0.346:1:0.803$ $H_4Ca(Si,Sn)_4O_{11}$

PHYS. CHAR. Crystals pyramidal, resembling gypsum. Cleavage perfect || 110, imperfect || 010. H. = 6. G. = 3.185.

OPT. PROP. The optic plane is parallel to 010; the acute bisectrix Z is normal to 001. Dispersion $\rho < v$. Colorless.

$$(+)\ 2V = 69^\circ\ 30' \quad (2E = 134^\circ)$$

$$n_g = 1.619 \quad n_m = 1.6125 \quad n_p = 1.609$$

$$n_g - n_p = 0.010$$

OCCUR. Found with axinite in Cornwall. Very rare.

**STRUVITE.**

ORTHORHOMBIC $a:b:c::0.566:1:0.912$ $NH_4MgPO_4 + 6H_2O$

PHYS. CHAR. Crystals hemimorphic, varied in habit. Twinning on 001. Cleavage perfect || 001, imperfect || 010. H. = 2. G. = 1.65-1.7. Easily fusible with green flame. Soluble.

Opt. Prop. The optic plane is parallel to 001; the acute bisectrix Z is normal to 010. Optic angle somewhat variable; dispersion $\rho < v$ marked.

$$(+)\ 2E = 42°\text{-}60°, \text{ usually } 60° \pm$$
$$n_m = 1.502$$

Colorless, yellowish, brown. Luster vitreous.

Occur. Found especially in guano; easily produced artificially.

**SULPHOBORITE**, see kieserite.

### SULPHUR.

Orthorhombic $a : b : c :: 0.813 : 1 : 1.903$ S

Phys. Char. Crystals usually pyramidal; also thick tabular, or modified. Massive, stalactitic, pulverulent, encrusting. Twinning on 101 sometimes interpenetrated; also on 110 or 011 rare. Cleavage imperfect || 001, 110 and 111. H. = 1.5-2.5. G. = 2.05-2.09. Melts at 108° C. and burns at 270° C. Insoluble in acids; soluble in $CS_2$.

Opt. Prop. The optic plane is parallel to 010; the acute bisectrix Z is normal to 001. Refringence very high; birefringence extremely strong. Optic angle large; dispersion $\rho < v$.

$$(+)\ 2V = 69°\ 5'$$
$$n_g = 2.2405 \quad n_m = 2.0383 \quad n_p = 1.9505$$
$$n_g - n_p = 0.290$$

Color yellow; rarely brownish, greenish, grayish. Streak white. Luster resinous.

Alter. Sulphur oxidizes slowly to sulphurous and sulphuric acids which yield sulphates.

Occur. Found especially in deposits of gypsum; also abundant about volcanoes. Less abundant in coal deposits, veins, etc., as a result of reduction of sulphides or sulphates. Deposited by some hot springs.

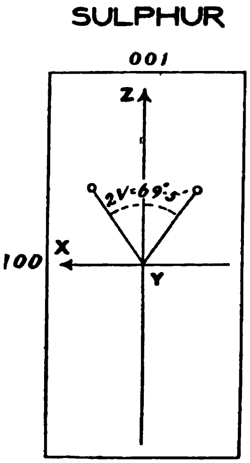

Figure 197. Optical orientation of sulphur.

**SYLVITE**, see halite group. **SYMPLESITE**, see vivianite. **SYNADELPHITE**, see flinkite. **SYNCHYSITE**, see parisite.

### SYNGENITE.

Monoclinic $a : b : c :: 1.370 : 1 : 0.874$ $K_2Ca(SO_4)_2 + H_2O$

$\beta = 76°\ 0'$

**Phys. Char.** Crystals prismatic, flattened || 100. Twinning on 100. Cleavage perfect || 110 and 100. H. = 2.5. G. = 2.6. Melts over Bunsen burner with violet flame. Partly soluble in $H_2O$.

**Opt. Prop.** The optic plane and the obtuse bisectrix Z are normal to 010; $X \wedge c = +87°$. Dispersion $\rho < v$ marked. Colorless to white.

$$(-)\ 2E = 44°\ 23' \quad (2V = 26°\ 44')$$
$$n_g = 1.5183 \quad n_m = 1.5170 \quad n_p = 1.5000$$
$$n_g - n_p = 0.0183$$

**Occur.** Found in salt mines with halite, gypsum and anhydrite. Rare.

## TALC.

Orthorhombic or monoclinic (?) $H_2Mg_3(SiO_3)_4$

Axial ratio unknown

**Phys. Char.** Crystals unknown except rare tablets hexagonal or rhombic in outline, which may be grouped in rosettes. Usually in more or less compact foliated masses; also somewhat granular, fibrous, or cryptocrystalline. Cleavage perfect || 001; laminæ flexible and elastic. Percussion figure as in the micas, but with its lines perpendicular to the faces 010, 110 and 1$\bar{1}$0. Twinning rare, producing pseudocubic forms. H. = 1. G. = 2.7-2.8. Fusible after whitening and exfoliation at 6 to white enamel. Insoluble.

**Opt. Prop.** The plane of the optic axes is parallel to 100; the negative acute bisectrix is nearly or quite normal to 001. Refringence moderate; birefringence strong. The optic angle is small, but the apparent angle is sometimes reduced even to 0° by superposition of laminæ. Axial dispersion noticeable, $\rho > v$. Colorless in thin section.

$$(-)\ 2E = 6° \text{ to } 40°.$$
$$n_g = 1.589 \quad n_m = 1.589(?) \quad n_p = 1.539$$
$$n_g - n_p = 0.050 \text{ to } 0.035$$

Color pale green, white, greenish gray to dark green; reddish by alteration. Luster pearly. Colorless in thin section.

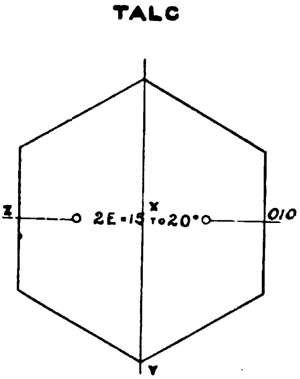

Figure 198.
Optical orientation of talc.

**Occur.** Talc occurs most abundantly in crystalline schists, where it may form rock masses (*steatite*, or soapstone) with other minerals, as tremolite, chlorite, present merely as impurities. It is found in other rocks, as serpentine, chlorite schist, dolomite. In basic igneous rocks it is an alteration product of olivine, enstatite, tremolite, but is not common.

**Thalite**[*] is a related mineral found in basic amygdaloidal rocks of the Lake Superior region; analyses show 43 to 48% $SiO_2$, 5 to 7% $Al_2O_3$, 2.1 to 2.6 $Fe_2O_3$, 23.3-24.1 MgO, 0.55-0.81 $Na_2O + K_2O$, 16 to 20% $H_2O$. It is finely fibrous, amorphous in appearance, with H. = 1.5 and G. = 2.20. Color white to gray. It gelatinizes with HCl. Usually contains foreign inclusions. Optically, the mineral is distinctly fibrous, and somewhat vermicular. The sign of the elongation and of the mineral is positive. The extinction seems to be parallel. The optic angle is small.

DIAG. Talc differs from pyrophyllite and muscovite in its small optic angle; it differs from brucite in its sign and biaxial character, as well as its insolubility. Talc is not readily distinguished optically from damourite (or sericite), but its indices of refraction are somewhat lower; other distinctions are based on hardness and chemical composition.

### TARBUTTITE.

TRICLINIC $a : b : c :: 0.9583 : 1 : 1.3204$ $Zn_2(OH)PO_4$

$$\alpha = 102° 37' \quad \beta = 123° 52' \quad \gamma = 87° 25'$$

PHYS. CHAR. Crystals varied in habit, with pinacoids or pyramids prominent. Often in sheaf-like aggregates. Cleavage perfect || 001. H. = 3.5-4. G. = 4.12. Soluble in dilute HCl. Readily fusible.

OPT. PROP. The optic plane makes angles in 001 of 33° with *b* and 55° with *a*; the acute bisectrix X is inclined about 40° to a normal to 001 toward $\bar{2}11$. Extinction in 010 makes angles of 25° with *a* and 10° with *c*; in 100 it makes angles of 26° with *c* and 14° with *b*. Refringence high; birefringence very strong.

$$(-) \quad 2E = 80° \text{ to } 90°$$

$$n_g > 1.706 \quad n_m = ? \quad n_p < 1.665$$

$$n_g - n_p > 0.041$$

Colorless or tinted green by copper or yellow or brown by iron.

OCCUR. Found in cellular limonite in zinc ores in Rhodesia; also with bones; rare.

### TELLURITE.

ORTHORHOMBIC $a : b : c :: 0.457 : 1 : 0.469$ $TeO_2$

PHYS. CHAR. Crystals prismatic, acicular, or tabular || 010 Also in tufts or radiated masses. Cleavage perfect || 010. Flexible. H. = 2. G. = 5.9. Fusible. Sublimes at high temperature.

OPT. PROP. The optic plane is parallel to 100; the acute bisectrix X is normal to 010. Refringence very high. $2H_a = 140° 8'$. Color white to yellow.

---

[*] N. H. Winchell. *Amer. Geol.* XXIII. 1899, p. 41.

OCCUR. Found with native tellurium in veins. Very rare.

**TEPHROITE,** see olivine group.

## TETRAHEDRITE.

ISOMETRIC $Cu_8Sb_2S_7$

COMP. Arsenic is usually present and thus there is a gradation to *tennantite* ($Cu_8As_2S_7$), which is included in the description following. Further, more or less copper may be replaced by iron, zinc, silver, mercury, lead, or rarely cobalt or nickel.

PHYS. CHAR. Crystals tetrahedral, often modified. Massive granular. Twinning on 111, or rarely 100. Cleavage none. H. = 3.-4.5. G. = 4.4-5.1. Easily fusible. Decomposed by $HNO_3$.

OPT. PROP. Opaque to translucent. Color gray to iron black, rarely purple. Streak gray to brown or red. In thin section bright red to opaque. Luster metallic, often splendent.

OCCUR. Found chiefly in veins with other copper ores, and with pyrite, galena, sphalerite, and various silver and gold ores.

## THALÉNITE

MONOCLINIC $a : b : c :: 1.154 : 1 : 0.602$ $H_2Y_4Si_4O_{15}$

$$\beta = 80° 2'$$

PHYS. CHAR. Crystals tabular || 100 or prismatic. Cleavage absent. H. = 6.5. G. = 4.23.

OPT. PROP. The optic plane and the obtuse bisectrix Z are normal to 010; the acute bisectrix is nearly normal to 100. Color flesh red.

$$(-)\ 2V = 67° 35'$$

$$n_g = 1.7436 \quad n_m = 1.7375 \quad n_p = 1.7312$$

$$n_g - n_p = 0.0124$$

OCCUR. Found with fluocerite in Sweden. Very rare.

## THAUMASITE.

HEXAGONAL Axial ratio unknown $CaCO_3 \cdot CaSO_4 \cdot CaSiO_3 \cdot 15H_2O$

PHYS. CHAR. Prismatic fibers; also massive, compact, crystalline. Cleavage longitudinal in traces. H. = 3.5. G. = 1.877. Infusible, but swells before the blowpipe and colors the flame red. Decrepitates and gives water in closed tube. Soluble with effervescence in acids.

OPT. PROP. Uniaxial and negative. Refringence quite low, but birefringence strong. Elongation negative.

$$n_g = 1.507 \quad n_p = 1.468$$

$$n_g - n_p = 0.039$$

Color white; luster greasy, dull. Colorless in section.

OCCUR. Rare; found as vein material in eclogite in Sweden.

DIAG. The very low indices of refraction with strong double refraction and uniaxial negative characters are quite distinctive.

## THENARDITE.

ORTHORHOMBIC $a:b:c::0.598:1:1.252$ $Na_2SO_4$

PHYS. CHAR. Crystals pyramidal, short prismatic, or tabular || 001. H. = 2.-3. G. = 2.68-2.69. Gives yellow flame color. Soluble in $H_2O$.

OPT. PROP. The optic plane is parallel to 001; the acute bisectrix Z is normal to 100. Optic angle very large; dispersion $\rho > v$ weak. Color white.

$$(+) \quad 2E = 152° 42' \text{Li} \quad (2V = 83° 5' \text{Li})$$
$$n_m = 1.470$$

OCCUR. Deposited from salt lakes, often associated with hanksite, glauberite, ulexite, etc. Also formed about volcanoes.

**THOMSENOLITE,** see cryolite. **THOMSONITE,** see zeolite group. **THORITE,** see rutile group.

## TITANITE (Sphene).

MONOCLINIC $a:b:c::0.7545:1:0.8543$ $CaTiSiO_5$
$\beta = 60° 17'$

PHYS. CHAR. Crystals often wedge shaped and flattened || 001, but the forms are very varied. They may be elongated || *c*, or || *a*, or simple pyramidal forms. Sometimes massive. Twinning plane often 100; also 221, in polysynthetic lamellæ, giving an easy parting. Cleavage distinct || 110, difficult || 100 and $\bar{1}12$. Parting || 221 due to twinning lamellæ. H. = 5.-5.5. G. = 3.4-3.56. Fusible at 3. Imperfectly soluble in HCl; reacts for Ti. Completely soluble in $H_2SO_4$.

OPT. PROP. The optic plane is parallel to 010; the positive acute bisectrix is nearly normal to 102 and therefore makes an angle of about 51° with the cleavage. The refringence is very high, and the birefringence extremely strong. The angle of the optic axes is very variable, but usually small. The axial dispersion is very strong, $\rho > v$; the inclined dispersion is slight.

$$(+) \quad 2V = 29° 30' \text{Li} \quad 27° \text{Na} \quad 24° 37' \text{Tl}$$
$$(2E = 32°\text{-}88°)$$
$$n_g = 2.0093 \quad n_m = 1.8940 \quad n_p = 1.8879$$
$$n_g - n_p = 0.1214$$

Color brown, yellow, gray, green, rose red, black, often varying in a single

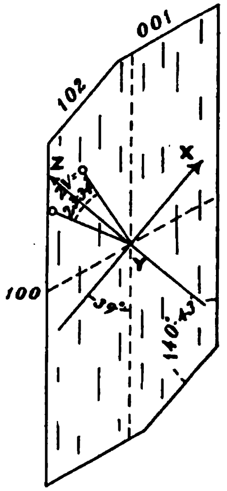

Figure 199.
Optical orientation of titanite.

crystal. Streak white. Pleochroism usually not strong in thin section, but deeply colored varieties exhibit intense pleochroism, and thick sections always show change of colors, thus:—
Z = salmon pink, pale yellow, orange to brownish red.
Y = greenish pink, pale brownish yellow, greenish yellow.
X = greenish yellow, pale brownish yellow, nearly colorless.

INCL. Ripidolite is sometimes found as inclusions in titanite; these may be grouped at the center of the enclosing crystal; albite is also found.

ALTER. Titanite alters in several ways. It may lose its color, become softer, and turn into a light yellow amorphous mass accompanied by calcite. It may be replaced by an opaque iron oxide with more or less ilmenite, rutile, octahedrite, calcite, etc. Rarely, perovskite and calcite replace it; in one case brookite formed from it.

OCCUR. Titanite is very widely distributed in rocks of all kinds. It is particularly at home in hornblende granites, syenites and diorites of the igneous rocks; the alteration product called leucoxene, which is supposed to be titanite, and is derived from ilmenite or titaniferous magnetite, is common in more basic rocks. Titanite is also common in crystalline schists, gneiss, etc. It is rare in sedimentary rocks. The finest crystals occur in drusy cavities.

**Keilhauite** is a variety of titanite containing notable amounts of ferric iron, aluminum, yttrium, and related rare earths. Crystals like those of titanite. Cleavage distinct || 111. H. = 6.5. G. = 3.52-3.77. Fusible easily with intumescence. Optically like titanite in all respects, but optic angle larger. $2E = 108° 34'$. Found in feldspathic rock in Norway. Very rare.

DIAG. Titanite is characterized by its forms, its very high relief, extreme birefringence, positive sign and biaxial character.

**TITANOLIVINE,** see olivine group.

## TOPAZ.

ORTHORHOMBIC $a : b : c :: 0.5285 : 1 : 0.477$ $[Al(F,OH)_2]AlSiO_4$

PHYS. CHAR. Crystals usually prismatic often vertically striated. In rocks usually in parallel or divergent groups of prisms. Also granular. Cleavage highly perfect || 001; difficult || 201 and 021. H. = 8. G. = 3.532-3.574, decreasing with increase of hydroxyl present*. Infusible. Only slightly attacked by $H_2SO_4$.

OPT. PROP. The plane of the optic axes is parallel to 010; the positive acute bisectrix is normal to 001, the cleavage. The birefringence varies in the same way. The indices of refraction increase with increase of hydroxyl. The angle of the optic axes varies, decreasing with increase of hydroxyl present.* Axial dispersion distinct with $\rho > v$.

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* Penfield and Minor, *Amer. Jour. Sci.* 1894 XLVII. p. 387.

$$(+)2V = 49° - 65°$$

| | Utah | Adun Tschalon | Schneck-enstein | Minas Geraes |
|---|---|---|---|---|
| $2E =$ | $125°53'$ | $118°46'$ | $114°28'$ | $84°28'$ |
| $n_g =$ | 1.6176 | 1.6225 | 1.6250 | 1.6375 |
| $n_m =$ | 1.6104 | 1.6160 | 1.6181 | 1.6308 |
| $n_p =$ | 1.6072 | 1.6133 | 1.6155 | 1.6294 |
| $n_g - n_p =$ | 0.0104 | 0.0092 | 0.0095 | 0.0081 |
| $H_2O =$ | 0.19 | 0.58 | 0.93 | 2.45 |
| G. = | 3.565 | 3.562 | 3.555 | 3.532 |

Colorless, yellow, white, grayish, greenish, bluish, reddish. Colorless in thin section.

INCL. Topaz often contains abundant liquid inclusions, which have been considered to be water and carbon dioxide; Nordenskjöld finds instances of a liquid believed to be a carbide of hydrogen. These liquids often contain minute crystals of unknown composition. Other inclusions in topaz include ilmenite and hematite.

**TOPAZ**

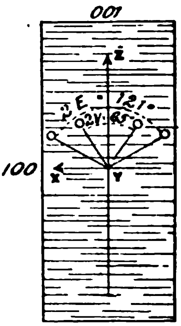

Figure 200. Optical orientation of topaz.

ALTER. Topaz may alter to kaolinite or to damourite.

OCCUR. Topaz occurs especially in zones of contact metamorphism, and in pegmatite. It is commonly associated with cassiterite, flourite, tourmaline, beryl, etc. It also occurs in cavities in rhyolite, with spessartite.

DIAG. Topaz is distinguished from andalusite by its cleavage and its smaller optic angle, from sillimanite by its weaker birefringence, different cleavage direction, higher relief, and biaxial character; and from orthoclase by its higher relief, absence or rarity of twinning and extinction parallel with the cleavage.

## TORBERNITE.

TETRAGONAL $c = 2.936$ $Cu(UO_2)_2(PO_4)_2 + 8H_2O$

PHYS. CHAR. Crystals usually square basal tablets; sometimes pyramidal. Also in foliated aggregates. Cleavage perfect || 001. H. = 2.-2.5. G. = 3.4-3.6. Fusible at 2.5 with green flame color. Soluble in $HNO_3$.

OPT. PROP. Uniaxial and negative. Refringence; $n_g = 1.592$, $n_p = 1.582$; $n_g - n_p = 0.010$. Color light to dark green; streak paler.

OCCUR. Found in veins in schists and granites. Rare.

**Zeunerite** $[Cu(UO_2)_2(AsO_4)_2 + 8H_2O]$ is closely related to torbernite, with $c = 2.913$. Crystals like torbernite. Cleavage perfect || 001, distinct || 100. H. = 2.-2.5. G. = 3.2. Soluble in $HNO_3$. Uniaxial and negative. Refringence, $n = 1.64$. Color apple green to emerald green. Found on quartz with copper ores. Very rare.

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* Penfield and Minor, *Amer. Jour. Sci.* 1894. XLVII. p. 387.

## TOURMALINE.

HEXAGONAL $c = 0.44767$ $R_6SiO_5$?

COMP. Tourmaline is a mineral of complex composition and its precise formula is still a matter of discussion. The detailed formulas proposed by various authors do not harmonize, but they all vary little in their simplest terms from that given above, in which R represents variable proportions of Al and B, with also either magnesium, iron, or an alkali metal; basic hydrogen or hydroxyl and fluorine are also present nearly always. The variations lead to three chief types, briefly described as alkali tourmaline, iron tourmaline, and magnesium tourmaline. A chromium variety is also known.

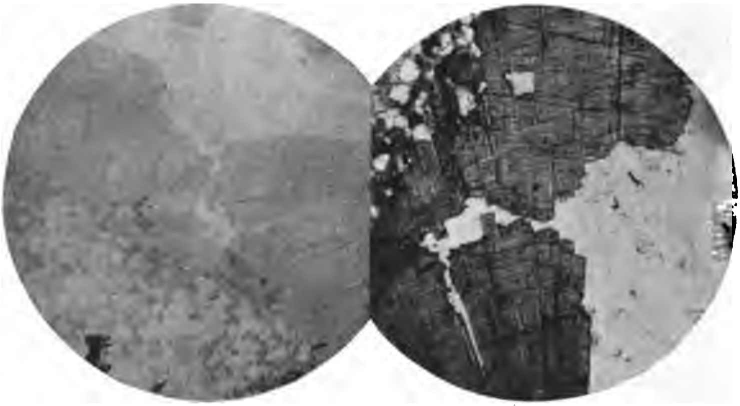
PHYS. CHAR. Crystals usually prismatic more or less elongated, but also rarely so short as to be lenticular. Vertical faces often deeply striated vertically. Commonly hemimorphic. Also found in crystalline aggregates, often in radiating groups. Twinning rare. Cleavage difficult $\parallel 11\bar{2}0$ and $10\bar{1}1$. Brittle. H. = 7.-7.5. G. = 2.9-3.2. Magnesium tourmaline fuses rather easily to a white or gray blebby slag or glass; iron tourmaline fuses with difficulty to a dark slag; the alkali tourmaline is usually infusible. Insoluble even in HF. After fusion gelatinizes with HCl.

OPT. PROP. Tourmaline is uniaxial and negative. Refringence medium and birefringence moderate. According to Lacroix of the three common varieties lithium tourmaline has the weakest birefringence and intermediate refringence; Wülfing assigns to magnesium tourmaline intermediate birefringence and the lowest refringence, and to iron tourmaline the strongest birefringence and the highest refringence. The rare chromium tourmaline has higher refringence and much stronger birefringence than any other variety.

| | Li tourmaline | Mg tourmaline | Fe Tourmaline | |
|---|---|---|---|---|
| | | | Blue | Green |
| $n_g =$ | 1.6377-1.6507 | 1.6315-1.6536 | 1.6517-1.6664 | 1.6424-1.6854 |
| $n_p =$ | 1.6199-1.6257 | 1.6123-1.6290 | 1.6281-1.6368 | 1.6222-1.6515 |
| $n_g - n_p =$ | 0.0146-0.0211 | 0.0192-0.0246 | 0.0236-0.0299 | 0.0202-0.0339 |

For Cr tourmaline $n_g = 1.687$, $n_p = 1.641$, $n_g - n_p = 0.046$.

Color black, bluish black, dark brown, less commonly blue, green, red, pink, colorless. Single crystals may vary in color. The pleochroism of the tourmaline is quite variable in intensity, but the absorption is always O>E, which may be ex-



Figures 201, 202. Photomicrographs of a tourmaline crystal in two positions, first with *c* parallel with the polarizer, second with *c* normal to the polarizer, showing strong absorption in the second position. From a section of pegmatitic granite from Wheal Tremayne, Cornwall. U. W. 729. One nicol. × 45.

pressed in this case as Z>X. Therefore the maximum absorption occurs when the vertical axis (and elongation) is at right angles with the vibration plane of the polarizer. Examples of the pleochroic formulas follow:—

| | Z(O) | X(E) |
|---|---|---|
| Sections 1.5 mm. thick. | | |
| Li tourmaline | pink, pale green, or greenish blue | colorless or nearly so |
| Mg tourmaline | dark yellowish brown | pale yellow |
| Sections 0.03 mm. thick. | | |
| Li tourmaline | colorless, pink, or very pale blue | colorless |
| Mg tourmaline | pale yellow | colorless |
| Fe tourmaline | yellowish brown to black | pale yellow to dark |
| Fe tourmaline | dark green | reddish violet to brownish |
| Fe tourmaline | blue of various shades | pale violet gray, yellowish or colorless |
| Cr tourmaline | green to bluish green | yellow |

A single crystal may have different colors irregularly distributed or arranged in zones, or at opposite ends of the vertical axis.

Incl. Very intense pleochroic colors may be present about inclusions of zircon or rutile; they are often of different color from that shown by the enclosing mineral; in them the birefringence is increased. They disappear when subjected to heat.

Alter. Tourmaline is usually unaltered in rocks; it may, however, change to a colorless mica with the characters of damourite; in other cases this is accompanied by biotite and sometimes chlorite.

Occur. Tourmaline occurs widely distributed in crystalline schists, gneiss, etc., as well as in phyllites, clay slates, and limestone. It is a common product of contact metamorphism resulting from the action of mineralizing vapors upon rocks of all types. It is frequent in pegmatites, granulites, and in veins. It occurs occasionally apparently as a primary constituent of acid igneous rocks.

Diag. Tourmaline is readily distinguishable from all other minerals by its pleochroism with maximum absorption perpendicular to the elongation, by its forms, its lack of cleavage, its distinct relief and bright interference colors, and its uniaxial negative character.

**TREMOLITE,** see amphibole group.

## TRIDYMITE.

Hexagonal at 130°C. $c. = 1.653$ $SiO_2$

Phys. Char. Crystals usually minute hexagonal plates parallel to the base. At ordinary temperatures the hexagonal form becomes the result of twinning || 110 of orthorhombic (Lacroix) individuals similar to the common aragonite twins. Twinning of other types often also present, sometimes giving pseudoisometric forms. Cleavage indistinct parallel to the prism faces; parting parallel to the base. H. = 7. G. = 2.28-2.33. Soluble in boiling $Na_2CO_3$; otherwise like quartz.

Opt. Prop. The plane of the optic axes is parallel to 100; the positive acute bisectrix is normal to 001. The refringence is very low and the birefringence very weak.

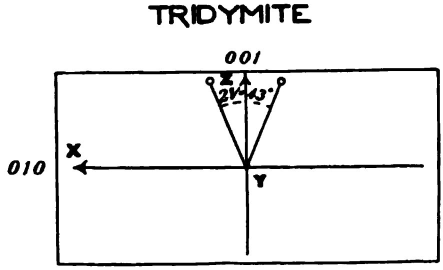


Figure 203. Optical orientation of tridymite.

$$(+)\ 2E = 66^\circ\ \ 2V = 43^\circ$$

$$n = 1.4775$$

$$n_g - n_p = 0.00185$$

Colorless or white. Colorless in section.

Incl. Gas inclusions are not infrequent.

Alter. Tridymite alters sometimes to quartz.

Occur. Tridymite is always formed at high temperatures; it is found in small aggregates and in crystals in lithophysæ, in siliceous lavas sometimes associated with opal. Also found in meteorites.

**TRIMERITE,** see phenacite group.

## TRIPHYLITE.

Orthorhombic $a:b:c::0.435:1:0.527$ $Li(Fe,Mn)PO_4$

Comp. By increase of manganese triphylite grades into **lithiophilite** $[Li(Mn,Fe)PO_4]$, which is included in the following description.

Phys. Char. Crystals prismatic, rare. Massive, cleavable to compact. Cleavage perfect || 001, imperfect || 010, interrupted || 110. H. = 4.5-5. G. = 3.42-3.56. Fusible at 1.5 with red flame having a bluish green border. Soluble in HCl.

Opt. Prop. The optic orientation changes with the varying amount of ferrous iron or manganese present. This is shown in the following table. The dispersion is very strong in all varieties, with $\rho < v$ in positive varieties and $\rho > v$ in negative varieties.

| Lithiophilite | | | Triphylite | |
|---|---|---|---|---|
| FeO 4.24 | FeO 9.42 | FeO 13.63 | FeO 26.58 | FeO 35.05 |
| $(+)2V=65°13'$ | $(+)62°54'$ | $(+)56°4'$ | $(+)2V=0°$ | $(-)2V=60°$ |
| $n_g =$ | 1.687 | | $n_g = 1.692$ | |
| $n_m = 1.675$ | 1.679 | 1.682 | $n_m = 1.688$ | 1.702 |
| $n_p =$ | 1.676 | | $n_p = 1.688$ | |
| $n_g - n_p =$ | 0.011 | | $n_g - n_p = 0.004$ | |
| $X \parallel a, Y \parallel c$ | $X \parallel a, Y \parallel c$ | $X \parallel a, Y \parallel c$ | $Z \parallel b$ | $X \parallel c, Y \parallel a$ |

In triphylite having 26.58% of FeO the optic angle about Z is 21°53′ in green light, 0° in yellow light, and 15° 3′ in red light. In green light the indices are:—$n_g = 1.698$, $n_m = 1.692$, $n_p = 1.691$. In red light the indices are $n_g = 1.691$, $n_m = 1.684$, $n_p = 1.683$. It is considered probable that in triphylite with more than 36% FeO the optic plane would be parallel to 010 and the sign still negative.

Color greenish gray or bluish in triphylite; color salmon pink, yellow, brown in lithiophilite; often black on the surface. Lithiophilite distinctly pleochroic with X deep pink, Y pale greenish yellow, Z pale pink.

Alter. These minerals alter readily by oxidation and hydration of manganese; alteration turns the minerals brown, red, or black, and develops three good cleavages. Ultimately pyrolusite may form.

Occur. Found in pegmatite, often associated with spodumene, triploidite, rhodochrosite.

**Natrophilite** $(NaMnPO_4)$ is isomorphous with triphylite and like it in all respects except deep wine yellow color and the composition.

**TRIPLITE,** see wagnerite.

### TRONA.

MONOCLINIC $a:b:c::2.846:1:2.970$ $HNa_3(CO_3)_2 + 2H_2O$
$\beta = 77° 23'$

PHYS. CHAR. Crystals tabular || 001 and elongated || *b*. Often fibrous, massive. Cleavage perfect || 100, in traces || 111 and 001. H. = 2.5-3. G. = 2.11-2.14. Effervesces with acids; soluble in $H_2O$. Taste alkaline.

OPT. PROP. The optic plane and the acute bisectrix X are normal to 010; Z makes an angle of 83° with *c*. Optic angle large; dispersion $\rho < v$ weak. Color gray or yellowish white.

$$(-)\ 2E = 137° 7'\ \ (2V = 76° 16')$$
$$n_m = 1.507$$

OCCUR. Found in salt lake deposits with halite, hanksite, thenardite, glauberite, etc.

### TYROLITE.

ORTHORHOMBIC $a:b:c::0.93:1:?$ $Cu_5(OH)_4(AsO_4)_2 + 7H_2O$

PHYS. CHAR. Crystals rare; usually radial or foliated masses. Cleavage perfect || 001. Flexible laminæ. H. = 1.-1.5. G. = 3.-3.1. Easily fusible. Soluble in $HNO_3$ or $NH_4OH$.

OPT. PROP. The optic plane is parallel to 010; the acute bisectrix X is normal to 001. Optic angle large. Refringence high, $n = 1.70$. Color pale to dark green, sometimes bluish. Streak paler. Luster pearly on 001, elsewhere vitreous.

OCCUR. Found in cavities in calcite, calamine, or quartz in copper deposits. Rare.

**Chalcophyllite** $[Cu_7(OH)_8(AsO_4)_2 + 10H_2O]$ is related to tyrolite, but it is rhombohedral with $c = 2.554$. Crystals six-sided tabular; also massive foliated. Cleavage perfect || 0001. H. = 2. G. = 2.4-2.66. Easily fusible. Soluble in $HNO_3$ or $NH_4OH$. Uniaxial and negative. Birefringence strong; $n_g = 1.6323$, $n_p = 1.5745$; $n_g - n_p = 0.0578$. Color dark green to grayish green. Streak paler. Found in copper mines often with clinoclasite, and derived from enargite. Rare.

### URANOCIRCITE

ORTHORHOMBIC Axial ratio unknown $Ba(UO_2)_2(PO_4)_2 + 8H_2O$

PHYS. CHAR. Crystals like autunite. Cleavage perfect || 001, distinct || 100 and 010. G. = 3.53.

OPT. PROP. The acute bisectrix X is normal to 001. $2E = 15°-20°$. Index $n = 1.62$. Color yellow green. Luster pearly on 001.

OCCUR. Found in quartz veins. Very rare.

**UVAROVITE,** see garnet group.

## VALENTINITE.

ORTHORHOMBIC $a:b:c::0.391:1:0.336$ $Sb_2O_3$

PHYS. CHAR. Crystals prismatic or tabular || 010, or elongated || $a$. Often in stellar or lamellar aggregates. Also massive, lamellar, granular, or columnar. Cleavage perfect || 010. H. = 2.5-3. G. = 5.57. Easily fusible, and somewhat volatile. Soluble in HCl.

OPT. PROP. The negative acute bisectrix is normal to 100; the optic plane is parallel to 001 in red light, and parallel to 010 in blue light. The optic angle is small, in yellow light nearly 0°. Refringence very high, $n = 2.34$ Na. Dispersion very strong, $\rho > v$, becoming $\rho < v$ when the axes for red and blue are in the same plane. When heated to 75°C. the optic angle in red light decreases somewhat, and in blue light increases.

Color snow white, rarely pink, gray, brownish. Colorless in thin section.

OCCUR. Formed by the alteration of stibnite or other antimony ores. Commonly mixed with cervantite and stibiconite.

**Claudetite** ($As_2O_3$) is closely related to valentinite in form and composition, but it is monoclinic with $a:b:c::0.404:1:0.345$ and $\beta = 86° 3'$. Crystals plates || 010 or prismatic. Twinning on 100 of penetration type common. Cleavage perfect || 010, giving flexible laminæ; fibrous separation || 110. H. = 2.5. G. = 3.85-4.15. Volatile. Optic plane parallel to 010; the acute bisectrix Z makes an angle of +6° with $c$. Dispersion $\rho < v$ strong. $2H = 65° 21'$. Colorless to white. Found in veins with arsenopyrite, in burning coal mines, and as an artificial product of smelting furnaces.

## VANADINITE, see apatite group.

## VESUVIANITE (Idocrase).

TETRAGONAL $c = 0.537$ $Ca_6[Al(OH,F)]Al_2(SiO_4)_5$

COMP. Other elements replacing those of the formula to variable amounts include iron, magnesium, manganese, sodium, titanium, etc.

PHYS. CHAR. Crystals commonly prismatic; sometimes pyramidal, or modified. Massive, columnar or granular. Cleavage indistinct || 110, in traces || 100 and 001. H. = 6.5. G. = 3.35-3.45. Fusible at 3. with intumescence. Partly decomposed by HCl.

OPT. PROP. Uniaxial and negative. Sometimes biaxial with optic angle variable, $2E = 30°-60°$. When biaxial, basal sections frequently show four diagonal sectors in each of which the optic plane is normal to the edge. The optic angle varies with the temperature, and in some cases with the pressure. *Viluite* is a rare variety which is positive. Refringence high; birefringence weak, usually about 0.004.

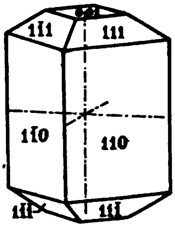


Figure 204. A simple crystal form of vesuvianite.

| | | | |
|---|---|---|---|
| Vesuvianite | $n_g = 1.705-1.732$ | $n_p = 1.701-1.726$ | $n_g - n_p = 0.001-0.006.$ |
| Viluite | $n_g = 1.717-1.721$ | $n_p = 1.716$ | $n_g - n_p = 0.001-0.005.$ |

Color brown to red, green, rarely yellow or pale blue. Streak white. In thin section colorless, pale brown, or green, the colors often distributed in zones or irregularly. Pleochroism usually not noticeable in thin section, but in thick plates the tints are quite variable, thus:—

| Mass color | Z | X |
|---|---|---|
| Brown | Yellow brown to yellow green | Brownish yellow to brownish gray |
| Red | Colorless to light gray | Light rose red to peachblow red |
| Green | Colorless to greenish yellow | Light flesh gray, yellow, or green |
| Blue | Dark blue | Nearly colorless |

OCCUR. Vesuvianite is found most abundantly in crystalline limestone metamorphosed by adjacent igneous rock; it is then usually closely associated with grossularite, diopside, wollastonite, epidote, etc. It occurs also in crystalline schists, in amphibole and in gneiss, and in quartz pegmatite veins in schists.

DIAG. Vesuvianite is characterized by high refringence, very weak birefringence, negative sign, negative elongation, crystal form, and frequent zonal arrangement of colors. It differs from zoisite in the absence of cleavage and abnormal dispersion, from gehlenite in its higher refringence and colors, from andalusite in its higher refringence and weaker birefringence, and smaller optic angle (when biaxial).

### VILLIAUMITE.*

PSEUDO-ISOMETRIC NaF?

PHYS. CHAR. Crystals unknown; massive, cleavable. Cleavage perfect || 001, distinct || 100 and 010. H. = 3.5. G. = 2.79. Soluble in hot $H_2O$.

OPT. PROP. Basal sections are apparently isotropic. Thick vertical sections show very weak birefringence, with X parallel to *c*. The refringence is extremely low; $n = 1.328$.

Color carmine red to dark violet, but becomes colorless when heated. In basal sections carmine red and non-pleochroic; in vertical sections carmine red parallel to the base, and golden yellow parallel to the vertical axis.

OCCUR. Found in nepheline syenites in French Guiana, apparently as a magmatic constituent. Very rare.

### VIVIANITE.

MONOCLINIC $a:b:c::0.750:1:0.702$ $Fe_3(PO_4)_2+8H_2O$

$\beta = 75° 34'$

PHYS. CHAR. Crystals prismatic, sometimes flattened || 100; often grouped. Commonly fibrous, divergent; also encrusting or earthy. Cleavage perfect || 010 (giving flexible laminæ), in traces || 100. H. = 1.5-2. G. = 2.58-2.68. Fusible at 1.5 with bluish green flame color to magnetic globule. Soluble in HCl.

---

* A. Lacroix. *C. R.* CXLVI. p. 213.

Opt. Prop. The optic plane and obtuse bisectrix X are normal to 010; Z makes an angle of 61½° with *c*. Birefringence strong. Optic angle large; slight horizontal dispersion with $\rho < v$ small.

$$(+)2E = 143° \ 14' \ (2V = 73° \ 10')$$

$$n_g = 1.6267 \quad n_m = 1.6050 \quad n_p = 1.5766$$

$$n_g - n_p = 0.050$$

Colorless when pure and unaltered, but usually blue to green. Streak colorless to bluish white, soon changing to dark blue or brown. Pleochroism strong when colored with Z = Y pale greenish yellow to colorless, X cobalt blue.

Alter. Alters easily by the oxidation of the iron.

Occur. Found in veins of copper, gold and tin with pyrrhotite and pyrite; also in clay beds; sometimes with limonite; often in cavities of bones or fossils.

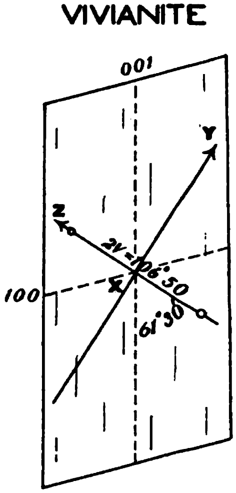


Figure 205.
Optical orientation of vivianite.

**Symplesite** ($Fe_3As_2O_8 + 8H_2O$) is isomorphous with vivianite, with $a:b:c::0.781:1:0.681$ and $\beta = 72° \ 43'$. Crystals prismatic or flattened || 010; radiated. Cleavage perfect || 010. H. = 2.5. G. = 2.96. Infusible. Optic plane and acute bisectrix X normal to 010; $Z \wedge c = +32°$. $2H_a = 107° \ 28'$. Color pale indigo blue to leek green. Streak bluish white. Pleochroism distinct with Z yellowish green, Y colorless to greenish yellow, X bluish green to blue. Found with siderite or pharmacosiderite. Very rare.

**Erythrite** ($Co_3As_2O_8 + 8H_2O$) belongs in the vivianite group; it has $a:b:c::0.75:1:0.70$ and $\beta = 75° \pm$. Crystals prismatic, vertically striated. Also globular, drusy, columnar, incrusting, earthy. Cleavage perfect || 010, indistinct || 100 and 101. Laminæ somewhat flexible. H. = 1.5 to 2.5. G. = 2.95. Fusible at 2. with light blue flame. Gives rose red solution with HCl. Optic plane and acute bisectrix X normal to 010. Z $c = 31°$. Birefringence strong. Optic angle large; slight crossed dispersion with $\rho > v$ weak. $2H = 104° \ 31'$; $n_g = 1.6986$; $n_m = 1.6614$, $n_p = 1.6263$; $n_g - n_p = 0.0723$. Color red, sometimes grayish green. Streak pale red; dry powder lavender blue. Pleochroism strong, red, green and blue. Formed by oxidation of cobalt ores; found in the surface part of veins. Rare.

**Annabergite** ($Ni_3As_2O_8 + 8H_2O$) is closely related to erythrite; crystals fibrous, massive; H. = 2.-2.5. G. = 3.08-3.13. Green solution in acids. Optic plane and acute bisectrix X normal to 010. $2H =$ 104°-107°, color green, pleochroic; streak greenish white. Produced from smalite, niccolite, etc. by oxidation. Very rare.

**Bobierrite** ($Mg_3P_2O_8 + 8H_2O$) is isomorphous with vivianite, with $\beta = 77° \pm$. Crystals six-sided prisms; crystalline masses. Cleavage || 010. H. = 1.-2. G. = 2.41. Soluble in acids. Optic plane and obtuse bisectrix X normal to 010; $Z \wedge c = 34° \pm$. $2E = 125° \pm$. Dispersion $\rho < v$ weak. Colorless to white. Found in guano. Very rare.

**Cabrerite** [$(Ni,Mg)_3As_2O_8 + 8H_2O$] is closely related to erythrite and bobierrite. Fibrous; radiated. Cleavage perfect || 010. H. = 2. G. = 2.96-3.11. Infusible. Optic plane and acute bisectrix X normal to 010; $Z \wedge c = -35°$. $2H = 105°-112°$ Li. Marked crossed dispersion with $\rho > v$ strong. Color apple green. Found with brown spar in limestone and schist in Spain; in zinc mines in Greece. Very rare.

**Hautefeuillite** [$(Mg,Ca)_3P_2O_8 + 8H_2O$] is closely related to bobierrite. Lamellar, radiated. Cleavage perfect || 010. H. = 2.5. G. = 2.44. Exfoliates and fuses. Soluble with difficulty. Optic plane parallel to 010; acute bisectrix Z makes an angle of 45° with $a$. $2E = 88°$. Strong inclined dispersion with $\rho < v$. $n = 1.52$. Colorless. Found with apatite, monazite, and pyrite. Very rare.

## WAGNERITE.

MONOCLINIC $a : b : c :: 1.9145 : 1 : 1.5059$ $(MgF)MgPO_4$

$$\beta = 71° 53'$$

PHYS. CHAR. Crystals sometimes coarse, vertically striated. Also massive. Cleavages difficult, not visible in thin sections. H. = 5.-5.5. G. = 2.98-3.07. Fusible at 4. to a greenish glass. Soluble.

OPT. PROP. The plane of the optic axes is parallel to 010; the positive acute bisectrix is almost parallel to $c$. The optic angle is small; axial dispersion marked $\rho > v$.

$$(+)\ 2V = 26° \pm$$

$$n_g = 1.582 \quad n_m = 1.570 \quad n_p = 1.569$$

$$n_g - n_p = 0.013$$

Color yellow, grayish, greenish, reddish. Colorless in thin section.

OCCUR. Found in granulites and in quartz veins; rare.

**Triplite** is a related mineral in which the magnesium is largely replaced by iron and manganese, with more or less calcium. It has two unequal cleavages at right angles. Color brown to brownish black. H. = 4.-5.5. G. = 3.44-3.8. Fuses at 1.5 to a black magnetic globule. Soluble. Triplite is positive like wagnerite, but it has a much larger optic angle ($2H = 95°$) and has distinct color and pleochroism in yellow to brown tints. In triplite the plane of the optic axes is nearly parallel to the imperfect cleavage and normal to the easy cleavage, while the positive acute bisectrix makes an angle of about 42° with the latter. It is often coated with pyrolusite by alteration; it occurs in quartz veins in granite often accompanied by apatite. Rare.

**Adelite** ($HCaMgAsO_5$) is probably related to wagnerite. It is monoclinic in tabular or prismatic crystals. Usually massive. Cleavage none. H. = 5. G. = 3.71-3.76. Fusible. Soluble. The acute bisectrix Z makes an angle of + 39° with *c*. Refringence, $n = 1.67$. $2E = 160° 40'$; dispersion $\rho > v$. Color gray. Luster resinous. Found in manganese mines in Sweden. Rare.

DIAG. Wagnerite is characterized by lack of cleavage, small optic angle, and weak birefringence; also by the presence of phosphorus and fluorine.

## WAPPLERITE, see pharmacolite.

## WARWICKITE.

ORTHORHOMBIC $a:b:c::0.977:1:?$ $(Mg,Fe)_4B_2TiO_9$

PHYS. CHAR. Usually in long prisms with rounded terminal faces. Cleavage good || 100. H. = 3.-4. G. = 3.35-3.42. Infusible. Decomposed by $H_2SO_4$; reacts for Ti.

OPT. PROP. The plane of the optic axes is parallel to 010: the positive acute bisectrix is normal to 100. The refringence is very high like that of titanite; the birefringence is only moderate.

$$(+)\ 2V = 70° \pm$$

$$n_g - n_p = 0.022$$

Color dark brown to black. In thin section the pleochroism is intense with Z = brown, Y = reddish brown, X = clear yellowish brown.

INCL. Warwickite commonly contains abundant inclusions of ilmenite and spinel.

ALTER. Alters to ilmenite.

OCCUR. Found in crystalline limestone; rare.

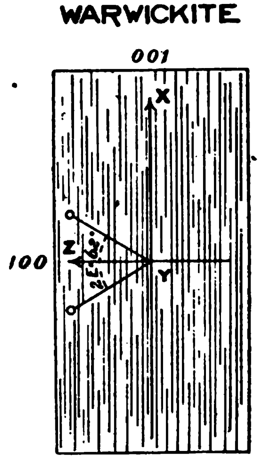


Figure 206. Optical orientation of warwickite.

DIAG. Distinguished from titanite by its much weaker birefringence and its intense pleochroism.

## WAVELLITE.

ORTHORHOMBIC $a:b:c::0.505:1:0.375$ $(AlOH)_3(PO_4)_2 + 5H_2O$

PHYS. CHAR. Crystals rare; usually in fibrous radiated aggregates. Cleavage distinct || 110 and 010, but usually not marked in aggregates. H. = 3.-4. G. = 2.3-2.5. Infusible, but swells and colors the flame green. Soluble.

OPT. PROP. The plane of the optic axes is parallel to 100; the positive acute bisectrix is normal to 001. Axial dispersion $\rho > v$. The extinction is parallel with the elongation, which is positive.

$$(+)\ 2V = 70° \pm$$
$$n_m = 1.526$$
$$n_g - n_p = 0.025.$$

Color white, yellow, pink, green, brown, black. Streak white. Colorless in thin section.

Occur. Found in granulites with amblygonite; also in phyllites and in veins.

**Augelite** [$Al(OH)_3AlPO_4$] is chemically related to wavellite. It is monoclinic, with $a:b:c::1.642:1:1.271$ and $\beta = 67° 34'$. Crystals tabular || 001, or prismatic. Cleavage perfect || 110, imperfect || $\bar{1}01$. H. = 4.5-5. G. = 2.7. Infusible. Nearly insoluble. Optic plane parallel to 010; acute bisectrix Z makes an angle of —34° with $c$. (+) $2E = 84° 42'$; $n_g = 1.5877$, $n_m = 1.5759$, $n_p = 1.5736$; $n_g - n_p = 0.0141$. Colorless to white. Found with lead and silver ores. Rare.

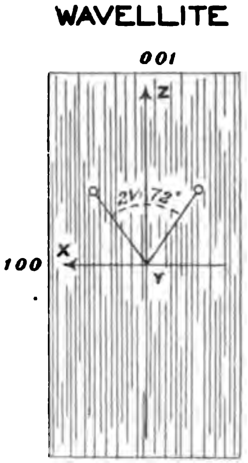


Figure 207. Optical orientation of wavellite.

Diag. Wavellite is commonly in fibrous radiated aggregates with low refringence, moderate birefringence, positive elongation, parallel extinction, and positive character. It contains phosphorus and water.

**WERNERITE,** see scapolite group. **WILLEMITE,** see phenacite group. **WITHERITE,** see aragonite group.

## WHEWELLITE.

Monoclinic $a:b:c::0.863:1:1.368$ $CaC_2O_4 + H_2O$

$$\beta = 73° 0'$$

Phys. Char. Crystals with numerous faces; prismatic faces vertically striated; often twinned on 101 in heart-shaped forms. Cleavage || 001, 010, 110. H. = 2.5. G. = 2.23.

Opt. Prop. The optic plane and the obtuse bisectrix X are normal to 010; Z ∧ $c$ = —11° or —12°. The birefringence is extremely strong. The optic angle is large; the crossed dispersion is weak, with $\rho < v$ also weak. Colorless.

$$(+)\ 2V = 84°$$
$$n_g = 1.6497 \quad n_m = 1.5552 \quad n_p = 1.4900$$
$$n_g - n_p = 0.1597$$

Occur. Found in crevices in bituminous coal with siderite. Rare.

## WOEHLERITE.

Monoclinic $a:b:c::1.0551:1:0.7092$ $Ca_{10}Na_5Si_{10}Zr_3Nb_2O_{42}F_3$

$$\beta = 70° 45'$$

Phys. Char. Crystals usually flattened || 100 with pinacoids, domes and the unit prism present. Twinning common with 100 as the twinning plane, often several lamellæ present. Also granular. Cleavage distinct || 010; very difficult || 110; fracture conchoidal abundant. H. = 6. G. = 3.14-3.44. Fusible to a yellow glass. Dissolves readily in HCl with separation of silica and $Nb_2O_5$.

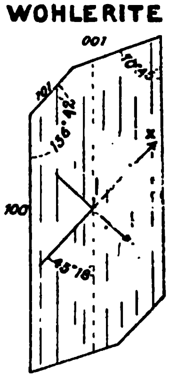


Figure 208. Optical orientation of wöhlerite.

Opt. Prop. The plane of the optic axes is perpendicular to 010 and nearly parallel with 101. The negative acute bisectrix makes an angle of about 45° with $c$ in the acute angle $\beta$. The angle of the optic axes is large. The refringence and the birefringence are about the same as in augite. Axial dispersion notable, $\rho < v$, and weak horizontal dispersion.

$$(-)\ 2V = 71°\text{-}79°$$

$$n_g = 1.726 \quad n_m = 1.716 \quad n_p = 1.700$$

$$n_g - n_p = 0.026$$

Color yellow. Colorless in thin section, but in thick section yellow and pleochroic; thus Z = deep wine yellow, Y = X = light wine yellow to colorless.

Occur. Rare; found in nepheline syenite in Norway.

Diag. Wöhlerite has less color and pleochroism than commonly found in låvenite, as well as a larger extinction angle. It differs from hiortdahlite in being monoclinic.

**WOLFRAMITE,** see hübnerite.

## WOLLASTONITE.

Monoclinic $a:b:c :: 1.0531 : 09676$ $CaSiO_3$

$$\beta = 84°\ 30'$$

Phys. Char. Crystals commonly tabular || 100 or 001, usually more or less elongated || $b$. Cleavage perfect || 100, less perfect || 001; sometimes distinct || $\bar{1}01$, and also $\bar{1}02$. Twinning on 100. G. = 2.8-2.9. H. = 4.5-5. Brittle. Fusible, but crystallizes on cooling. Soluble in acids with gelatinization.

Opt. Prop. The plane of the optic axes is parallel to 010, and therefore normal to the elongation. The negative acute bisectrix makes an angle of 38° with the basal plane in sections parallel with 010. Refringence high; birefringence moderate. Optic angle rather large. Inclined dispersion distinct, with $\rho > v$. Often in divergent fibers with cleavage parallel to the elongation, which is positive or negative.

$$(-)\ 2E = 70° \quad 2V = 40°$$

$$n_g = 1.635 \quad n_m = 1.633 \quad n_p = 1.621$$

$$n_g - n_p = 0.014$$

**WOLLASTONITE**

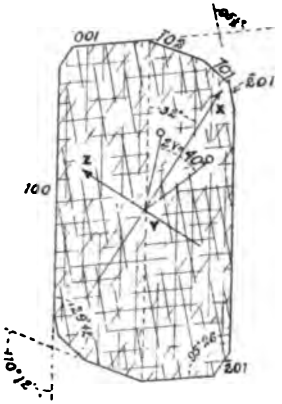


Figure 209.
Optical orientation of wollastonite.

Color white, gray, rarely yellow or reddish. Colorless in thin section.

ALTER. Wollastonite alters readily to calcite.

OCCUR. Found frequently in regions of contact between igneous rocks and limestones; also in limestone masses caught in volcanic rocks; also in crystalline limestones. It is often associated with augite, diopside, garnet, epidote, calcite; and these minerals occur as inclusions.

DIAG. Distinguished from pectolite and tremolite by the variable sign of the elongation and the weaker birefringence; from colorless epidote by lower refringence, weaker birefringence (epidote has variable birefringence, but always stronger than wollastonite), and smaller optic angle.

**WULFENITE,** see scheelite group. **WURTZITE,** see cinnabar group. **XANTHOCONITE,** see pyrargyrite. **XANTHOPHYLLITE,** see clintonite group.

## XENOTIME.

TETRAGONAL $c = 0.6187$ $YPO_4$

COMP. Yttrium often replaced by related elements, as erbium, also cerium; silicon and thorium may also be present.

PHYS. CHAR. Crystals short prisms as in zircon. Twinning on 101. Cleavage perfect || 110. H. = 4.-5. G. = 4.45-4.56. Infusible. Insoluble.

OPT. PROP. Uniaxial and positive. Refringence high.

$$n_g = 1.81 \quad n_p = 1.72$$
$$n_g - n_p = 0.090$$

Color yellowish brown, reddish brown, red, gray, yellow. Streak paler. Luster resinous to vitreous. In thin section colorless, yellowish, pale brownish.

OCCUR. Found in pegmatite veins in granite, gneiss, etc. Also in granite. Commonly associated with zircon, sometimes in parallel growths.

**Hussakite** is a phosphate of yttrium, erbium, etc., with sulphur, closely related to xenotime. Like xenotime in physical characters, except G. = 4.59. Uniaxial and positive. Refringence high; birefringence very strong. $n_g = 1.8155$, $n_p = 1.7207$; $n_g - n_n = 0.0948$. Color yellowish white to dark brown. Luster vitreous. In thin section colorless, yellowish, pale brownish. Sometimes weakly pleochroic with Z brownish yellow or grayish brown, X pink or light yellowish brown. Differs from xenotime in presence of $SO_3$, from cassiterite and zircon in lower refringence.

DIAG. Xenotime differs from zircon in hardness and composition; from cassiterite by weaker birefringence, from octahedrite by its sign (+).

**XYLOTILE,** see serpentine group.

### Zeolite Group.

The minerals of the zeolite group are closely related in many characters, but they are quite diverse in their crystal habits. One of the series (analcite) is isometric at 130° C. and pseudoisometric at ordinary temperatures, gismondite is pseudotetragonal and monoclinic; hydronephelite and the chabazite subgroup are hexagonal or pseudohexagonal, thomsonite, edingtonite, and natrolite are orthorhombic, mesolite is triclinic and the others are monoclinic. The zeolites are usually colorless or white except when colored by impurities. The hardness ranges from 3.5-5.5, and the specific gravity from 2. to 2.4; (edingtonite 2.7). These minerals are rather easily decomposed by acids, usually with gelatinization; they are readily fusible, and many of them intumesce before the blowpipe, a character which gives the name to the group.

OPT. PROP. The zeolites are wholly colorless in thin section (with the single exception of chlorastrolite); they are further characterized by low refringence, the mean index of refraction being in all cases less than that of Canada balsam, and usually less than that of orthoclase. Finally, with the exception of thomsonite (0.027) and the related lintonite 0.017, all the zeolites have weak birefringence ranging from 0.001 in the analcite to 0.012 in the hydronephelite, and 0.016 in edingtonite. The zeolites without apparent elongation are those which are apparently in the isometric, tetragonal, and hexagonal systems; heulandite and brewsterite have lamellar cleavage parallel to 010; all the others are commonly distinctly fibrous. The fibrous zeolites are often in radiated or spherulitic aggregates.

ALTER. Being themselves alteration products, the zeolites do not easily change to other minerals, but in some cases they have been observed to alter to kaolinite, or to calcite, or to an amorphous substance. Under other conditions they may be transformed to albite, or prehnite. By artificial fusion and recrystallization some of them will yield anorthite, or a calcium-albite.

OCCUR. The zeolites are practically always secondary minerals formed by the hydration of aluminum silicates of calcium, sodium, etc. They are derived chiefly from the feldspars, but also from nephelite, leucite, sodalite, etc. They are found especially in amygdaloidal cavities, fractures, and other openings in rocks of many types, but they are notably abundant in igneous rocks of the gabbro and basalt groups. They are found also in some metalliferous veins, especially where the gangue is limestone, and in the deposits of hot springs, where they have in some cases been formed within historic time and are undoubtedly now in process of formation. Finally, phillipsite is produced at great depths on the ocean bottom by the action of the salt water upon the basic volcanic dust beneath it. The zeolites are commonly associated with calcite, prehnite, pectolite, apophyllite, datolite.

DIAG. *Analcite* is at once distinguished from all other zeolites by its extremely weak birefringence; in fact it is often apparently isotropic. *Chabazite* and *gmelinite* are similar in having very weak birefringence; they have a variable but small optic angle of variable sign. *Gismondite* has a large optic angle about a negative bisectrix, and a birefringence of 0.008. Its exterior form is that of a tetragonal bipyramid produced by complex twinning of monoclinic individuals. *Hydronephelite* is uniaxial and positive, with a birefringence that is rather strong for a zeolite, viz. 0.012. *Heulandite* and *brewsterite* are usually more or less flattened parallel with the perfect cleavage (010), and more or less vertical elongation is frequent, especially in brewsterite. Both have the positive acute bisectrix perpendicular to the cleavage, whose direction is therefore negative. The optic angle is quite variable, but usually small, in heulandite; it is large in brewsterite. The maximum extinction angle in the vertical zone is very small in heulandite, while it is about 22° in brewsterite. *Edingtonite* has, for a zeolite, rather high relief and strong birefringence; the optic angle is large and of negative sign; crystals are minute, pyramidal.

The optical orientation of the remaining zeolites is shown in the accompanying diagram, in which the angle of extinction in sections parallel with 010 is given as measured on the vertical axis. This axis is the direction of elongation except in the case of ***phillipsite, harmotome*** and ***stilbite,*** in which the elongation is parallel with the clino axis. The maximum extinction angle measured on the axis of elongation is 11° to 30° in phillipsite, 28° in harmotome, and 5° in stilbite. The direction of elongation

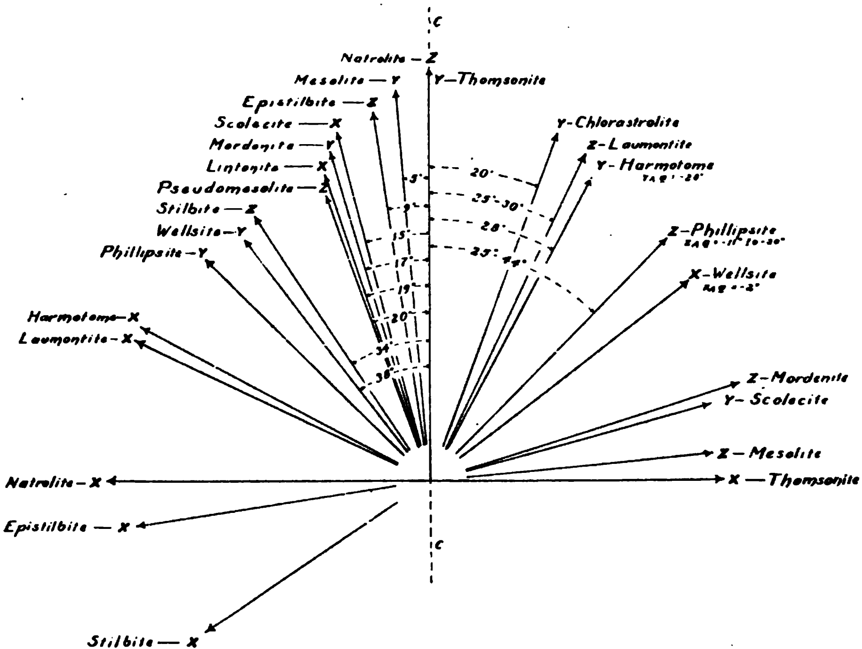


Figure 210. Diagram showing the extinction angles measured on *c* in the plane 010 for all zeolites with marked elongation. Angles measured to the right of *c* are in the acute angle $\beta$ and those to the left of *c* in the obtuse angle $\beta$, except in the case of chlorastrolite, mesolite, pseudomesolite, and lintonite; in these minerals the orientation with respect to $\beta$ is unknown.

is + in phillipsite, ± in harmotome, and — in stilbite. *Thomsonite* is readily distinguished from all other zeolites by its strong birefringence (0.027); its direction of elongation is ±, and it has parallel extinction. *Natrolite* has parallel extinction; its direction of elongation is +, and its birefringence is 0.012. *Scolecite* has elongation of negative sign, a maximum extinction angle of 15° or 16°, and a birefringence of about 0.008. *Mesolite* has a very small maximum extinction angle (5°), but the direction of elongation is ±, and the birefringence is about 0.004. *Pseudomesolite* has a maximum extinction angle of about 20°; its elongation is +, its birefringence is very weak (about 0.002), and its optic angle very small. *Laumontite* has one of the largest maximum extinction angles (25° to 30°) known in the zeolites as measured on the elongation, being equaled only by harmotome (28°) and phillipsite (11° to 30°), but the direction of elongation is + in laumontite and in phillipsite, and ± in harmotone, while the birefringence of laumontite is 0.012, of harmotome 0.005, and of phillipsite 0.003. *Epistilbite* has positive elongation and a small maximum extinction angle (9°), differing therefore in the sign of the elongation from stilbite (—) and mesolite (±) which also have small extinction angles; epistilbite has also distinctly stronger birefringence (0.010) than either stilbite (0.006) or mesolite (about 0.004). *Phillipsite* has also very weak birefringence (0.003). *Mordenite* and *lintonite* have maximum extinction angles of 17° and 19° only a little larger than scolecite, but mordenite is distinguished by the variable sign of the elongation and lintonite by its strong birefringence (0.017).

Class. The zeolites are classified as follows, beginning with the most acid:—

| | | |
|---|---|---|
| Mordenite<br>Ptilolite | Monoclinic | $(Ca,Na_2,K_2)Al_2Si_{10}O_{24} + 6\frac{2}{3}H_2O$ |
| Heulandite | Monoclinic | $CaAl_2Si_6O_{16} + 5H_2O$ |
| Brewsterite | Monoclinic | $(Sr,Ba,Ca)Al_2Si_6O_{16} + 5H_2O$ |
| Epistilbite | Monoclinic | $CaAl_2Si_6O_{16} + 5H_2O$ |
| Stilbite | Monoclinic? | $(Ca,Na_2)Al_2Si_6O_{16} + 6H_2O$ |
| Harmotome | Monoclinic | $(Ba,K_2)Al_2Si_5O_{14} + 5H_2O$ |
| Phillipsite | Monoclinic? | $(Ca,K_2)Al_2Si_4O_{12} + 4H_2O$ |
| Gismondite | (Pseudotetragonal) Monoclinic | $CaAl_2(SiO_3)_4 + 4H_2O$ |
| Laumontite | Monoclinic | $CaAl_2Si_4O_{12} + 4H_2O$ |
| Chabazite | (Pseudohexa.) Triclinic? | $(Ca,Na_2)Al_2(SiO_3)_4 + 6H_2O$ |
| Gmelinite | (Pseudohexa.) Triclinic? | $(Na_2,Ca)Al_2(SiO_3)_4 + 6H_2O$ |
| Analcite | Pseudoisometric | $NaAl(SiO_3)_2 + H_2O$ |
| Edingtonite | (Pseudotetragonal) Orthorhombic | $BaAl_2Si_3O_{10} + 3H_2O$ |
| Natrolite | (Pseudotetragonal) Orthorhombic | $Na_2Al_2Si_3O_{10} + 2H_2O$ |
| Scolecite | Monoclinic | $CaAl_2Si_3O_{10} + 3H_2O$ |
| Mesolite<br>and<br>Pseudomesolite | Triclinic<br><br>Triclinic? | $mNa_2Al_2Si_3O_{10} + 2H_2O$<br>$+$<br>$nCaAl_2Si_3O_{10} + 3H_2O$ |
| Thomsonite | Orthorhombic | $(Ca.Na_2)Al_2(SiO_4)_2 + 2\frac{1}{2}H_2O$ |
| Hydronephelite | Hexagonal | $HNa_2Al_3(SiO_4)_3 + 3H_2O$ |

## MORDENITE.

Mono. $a:b:c::0.401:1:0.428$ $(Ca,Na_2,K_2)Al_2Si_{10}O_{24} + 6\frac{2}{3}H_2O$
$\beta = 88° 30'$

Phys. Char. Crystals usually flattened parallel to 010, sometimes in groups parallel to 010; also fibrous, arranged at times radially in reniform and cylindrical masses. Cleavage perfect || 010. H. = 3-4. G. = 2.08-2.15. Fusible slowly without intumescence to white enamel. Not wholly decomposed by acids.

Opt. Prop. The plane of the optic axes and the bisectrix X are perpendicular to 010; the bisectrix Z makes an angle of 73½° with the vertical axis in the acute angle $\beta$. The angle of the optic axes is large. The birefringence is weak.

Color white, yellowish, pinkish. Colorless in section.

Occur. Found in basalt in Nova Scotia and Wyoming. Rare.

**Ptilolite** is a very similar zeolite, always fibrous, with parallel extinction. It contains less water and more potash. The fibers have negative elongation. Birefringence very weak; $n_g < 1.485 > 1.480$, $n_p > 1.480$; $n_g - n_p < 0.005$. Occurs in Colorado. Rare.

Diag. Mordenite is characterized by having its optic plane and a bisectrix perpendicular to the plane of symmetry, which is marked by perfect cleavage.

## HEULANDITE.

Monoclinic $a : b : c :: 0.403 : 1 : 0.429$ $\beta = 88° 34'$ $CaAl_2Si_6O_{16} + 5H_2O$

Phys. Char. Crystals often flattened || 010; also equidimensional of orthorhombic aspect. Crystals may be composed of numerous subindividuals in nearly parallel position. Also globular, granular. Cleavage perfect || 010. H. = 3.5-4. G. = 2.18-2.26. Before the blowpipe exfoliates, swells, and curves into vermicular forms, fusing to a white enamel. Decomposed by HCl without gelatinization.

Opt. Prop. The plane of the optic axes is always perpendicular to 010, usually nearly parallel to 001, but sometimes nearly perpendicular to that face. In still other cases the optic plane makes widely varying angles with 001. The positive acute bisectrix is always perpendicular to 010. The angle of the optic axes is variable even in a single crystal. Axial dispersion weak $\rho < v$ when the optic plane is nearly parallel to 001, and $\rho > v$ when it is nearly perpendicular. Very distinct crossed dispersion. The optic plane in red light makes an angle of 7° to 12° with the same plane in blue light. The optic properties undergo several changes upon the application of heat. The refringence is low and the birefringence is weak.

$$(+)\ 2E = 0° \text{ to } 92°, \text{ usually } 52° \pm$$

$$n_g = 1.505 \quad n_m = 1.499 \quad n_p = 1.498$$

$$n_g - n_p = 0.007$$

After heating to 230°C. and thus expelling the water, the indices are:—$n_g = 1.4747$, $n_m = 1.4733$, $n_p = 1.4651$; $n_g - n_p = 0.0096$.

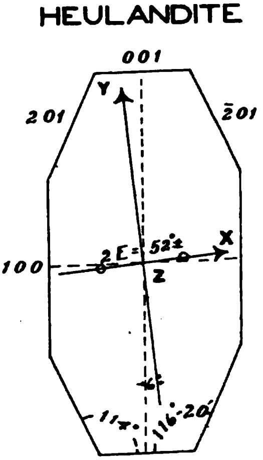


Figure 211.
Optical orientation of heulandite.

Color white, yellowish, or colored by impurities gray, brown or red. Colorless in section.

Occur. Heulandite is found especially in basaltic rocks, but occurs also in cavities and fractures in crystalline schists. It is usually associated with other zeolites.

Diag. Heulandite is rarely fibrous, but has a lamellar cleavage, with the positive acute bisectrix perpendicular thereto. Brewsterite is similar, but has a smaller optic angle and less dispersion of the bisectrices, as well as stronger birefringence. In stilbite the optic plane is parallel with the cleavage.

## BREWSTERITE.

MONO. $a:b:c::0.405:1:0.420$ $(Sr,Ba,Ca)Al_2Si_6O_{16}+5H_2O$

$\beta=86° 20'$

PHYS. CHAR. Crystals commonly prismatic, somewhat vertically elongated, and more or less flattened || 010; faces of the prism zone vertically striated. Cleavage perfect || 010, in traces || 100. H. = 5.-5.5. G. = 2.3-2.45. Before the blowpipe swells and fuses at 3. to white enamel. Decomposed by acids without gelatinization.

OPT. PROP. The plane of the optic axes and the positive acute bisectrix are perpendicular to 010; the axis X makes an angle of 22° with the vertical axis in the obtuse angle $\beta$ in simple crystals; in other crystals this angle is found to be about 19° in central parts and as much as 24°-34° in other parts. The optic angle is large. Axial dispersion is weak with $\rho>v$; crossed dispersion also weak. Refringence low; birefringence rather strong for a zeolite.

$$(+)\ 2E=93° \text{ to } 103°$$
$$n=1.45$$
$$n_g-n_p=0.012$$

Color white, yellowish or greenish. Colorless in section.

ALTER. Brewsterite sometimes alters to calcite.

OCCUR. Found in drusy cavities in crystalline schists and basalt.

DIAG. See heulandite.

## EPISTILBITE.

MONOCLINIC $a:b:c::0.504:1:0.580$ $CaAl_2Si_6O_{16}+5H_2O$

$\beta=54° 53'$

PHYS. CHAR. Crystals always twinned and prismatic; also in radiated spherical aggregates; granular. Twins sometimes penetration crosses. Twinning on 100, or 110. Cleavage perfect || 010. H. = 3.5-4.5. G. = 2.25. Before the blowpipe intumesces and forms a vescicular enamel. Imperfectly soluble in HCl without gelatinization.

OPT. PROP. The plane of the optic axes is parallel with 010; the obtuse bisectrix Z makes an angle of 9° with the vertical axis in the obtuse angle $\beta$. The elongation is therefore positive, with extinction at 0° to 9°. The angle of the optic axes is large. Distinct axial dispersion, $\rho<v$. Refringence low and birefringence rather weak. When heated the extinction angle gradually diminishes, and the mineral becomes finally orthorhombic, with Z || $c$ and X || $b$; upon reabsorption of water the process is reversed.

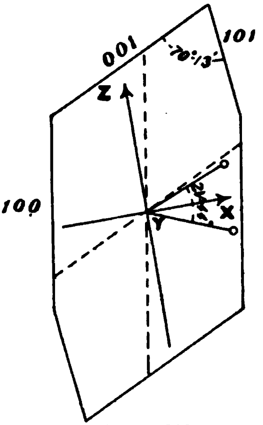


Figure 212.
Optical orientation of epistilbite.

$$(-)\ 2E = 70° - 75° \ (2V = 44°)$$
$$n_g = 1.512 \quad n_m = 1.510 \quad n_p = 1.502$$
$$n_g - n_p = 0.010$$

Colorless, white, pinkish, reddish. Colorless in section.

OCCUR. Commonly associated with stilbite, and other zeolites in cavities in crystalline rocks.

DIAG. Differs from stilbite and mesolite in the sign of the elongation, and has much stronger birefringence than phillipsite.

## STILBITE.

MONO. $a:b:c::0.762:1:1.194$ $(Ca,Na_2)Al_2Si_6O_{16} + 6H_2O$
$\beta = 50° 50'$

PHYS. CHAR. Crystals always twinned, as in phillipsite, with 001 as the twinning plane, producing pseudoorthorhombic forms. Usually flattened || 010; often grouped in sheaf-like aggregates which are characteristic. Also radiated or divergent, spherulitic, elongated || $a$. Cleavage perfect || 010, in traces || 001. H. = 3.5-4. G. = 2.09-2.20. Before the blowpipe exfoliates and opens to vermicular forms, and fuses to a white enamel. Decomposed by HCl without gelatinization.

OPT. PROP. The plane of the optic axes is parallel to 010, the negative acute bisectrix makes an angle of about 5° (from 0° to 10°) with $a$ in the obtuse angle $\beta$; the axis Z therefore makes an angle of about 34° with $c$ in obtuse angle $\beta$. The elongation parallel $a$ is therefore —. The angle of the optic axes is considerable. The refringence is low and the birefringence weak. Like phillipsite, and for a similar reason, stilbite is said to be actually triclinic. Upon heating it becomes strictly orthorhombic.

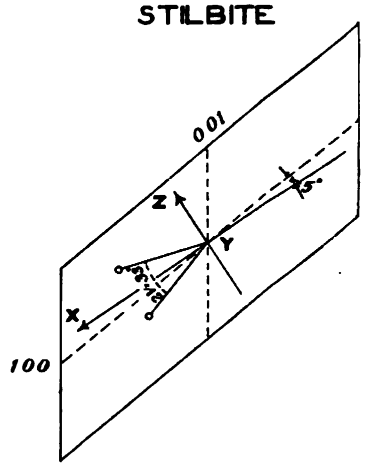


Figure 215.
Optical orientation of stilbite.

$$(-)\ 2E = 52° \pm \ (2V = 33° \pm)$$
$$n_g = 1.500 \quad n_m = 1.498 \quad n_p = 1.494$$
$$n_g - n_p = 0.006$$

Color white, yellowish, etc. from impurities. Colorless in section.

OCCUR. Stilbite is found in cavities in basaltic rocks;

it also occurs in fractures in acid igneous rocks, and in metamorphic rocks, especially gneiss. It is formed in some hot springs.

Diag. Distinguished from phillipsite and harmotome by its lamellar aggregates and lamellar cleavage, as well as by its extinction angles and the sign of the elongation. Heulandite has the positive acute bisectrix normal to the cleavage, while stilbite is negative and its optic plane is parallel with the cleavage.

### HARMOTOME.

Mono. $a : b : c :: 0.703 : 1 : 1.231$ $(Ba,K_2)Al_2Si_5O_{14} + 5H_2O$

$\beta = 55° \ 10'$

Phys. Char. Crystals very similar to those of phillipsite, but not as diversified. Elongated || *a*. Cleavage easy || 010, difficult || 001. H. = 4.5. G. = 2.44-2.50. Before the blowpipe whitens, crumbles and fuses without intumescence at 3.5 to a white glass. Decomposed by HCl without gelatinization.

Opt. Prop. The plane of the optic axes and the positive acute bisectrix are perpendicular to 010; the axis X makes an angle of 62° ± with *c* and with *a*, bisecting the obtuse angle $\beta$. The angle of the optic axes is large. Weak crossed dispersion. The elongation parallel to *a* is ±.

$(+) \ 2H = 87°$

$n_g = 1.508 \quad n_m = ? \quad n_p = 1.503$

$n_g - n_p = 0.005$

Colorless, white; yellowish by alteration.

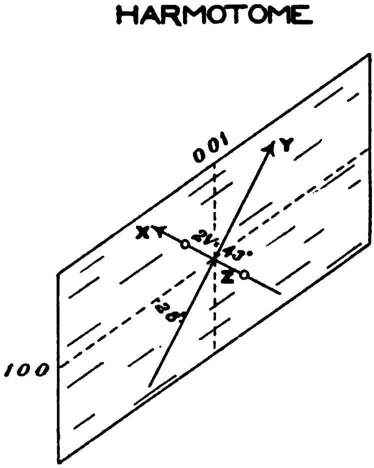


Figure 214.
Optical orientation of harmotome.

Occur. Harmotome occurs in basalt and also in acid igneous rocks; also in gneiss and in lead and zinc veins.

Diag. Distinguished from phillipsite by its optical orientation; also by greater specific gravity, and the presence of barium.

### PHILLIPSITE (Christianite).

Monoclinic? $a : b : c :: 0.7095 : 1 : 1.2563$ $(Ca,K_2)Al_2Si_4O_{12} + 4H_2O$

$\beta = 55° \ 37'$

Phys. Char. Crystals always penetration twins; in the simplest type the twinning plane is 001, and the crystal presents an apparent orthorhombic or tetragonal form. Frequently these simple twins are again twinned to form crosses with arms parallel to two or even three rectangular axes. Also found in radiating spherulites, the fibers elongated || *a*. Cleavage good || 001 and 010. H. = 4.-4.5. G. = 2.2. Fusible at 3. to a white enamel. Gelatinizes with HCl.

Opt. Prop. The plane of the optic axes and the obtuse bisectrix X are perpendicular to 010; the acute bisectrix Z makes an angle of 11° to 30° with *a* in the obtuse angle $\beta$; therefore $Z \wedge c = -25°$ to $-44°$. The elongation is + since it is parallel with *a*. While the exterior form of phillipsite is apparently monoclinic, the optical properties indicate a triclinic mineral, since sections parallel with 001 give extinction at more than 10° from the traces of 010. The angle of the optic axes is variable, but large. The axial dispersion is weak, $\rho < v$. The refringence is low and the birefringence very weak.

$$(+) \quad 2V = 62° \text{ to } 80°$$

$$n_m = 1.48\text{-}1.51$$

$$n_g - n_p = 0.003.$$

Colorless, white; yellowish or reddish by alteration. Colorless in thin section.

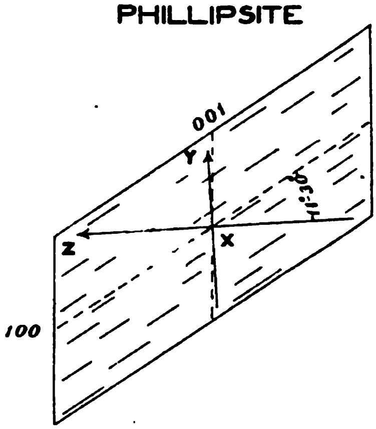


Figure 213.
Optical orientation of phillipsite.

Occur. Phillipsite occurs in druses of basalt and of other igneous rocks; it is rare in metamorphic rocks; it has been found abundantly in red clay, and other deep sea deposits, near Hawaii; it occurs of recent formation in some hot springs. It is especially associated with chabazite, but to some extent also with thomsonite, calcite, apophyllite.

**Wellsite** is a rare zeolite of the phillipsite group containing only $3H_2O$. Its crystals are like those of phillipsite, and its density is 2.3. Cleavage absent. Optically it is positive with a large axial angle; the acute bisectrix is normal to 010; $X \wedge c = -52°$; birefringence weak.

Diag. The twinning of phillipsite is quite characteristic except as compared with harmotome, which is rare and has different optical orientation.

## GISMONDITE.

Mono. Pseudotetragonal. Axial ratio unknown $CaAl_2(SiO_4)_2 + 4H_2O$

Phys. Char. Crystals always apparently tetragonal bipyramids; this form is produced by twinning on two laws. Fracture uneven. H. = 4.5. G. = 2.265. Before the blowpipe whitens, intumesces, and fuses to a milky glass. Easily soluble with gelatinization.

Opt. Prop. The negative acute bisectrix is perpendicular to 010; the axis Z is nearly normal to 100. The angle of the optic axes is large. The refringence is low, and the birefringence is weak. Upon heating it becomes orthorhombic, with the negative acute bisectrix parallel to *c* and a small optic angle.

$$(-)\ 2V = 82^\circ \text{ to } 83^\circ$$
$$n_m = 1.5385$$
$$n_g - n_p = 0.008$$

Colorless, white, grayish. Colorless in thin section.

OCCUR. Found in volcanic rocks with phillipsite, etc., in metamorphic crystalline rocks, and in basaltic rocks. Uncommon.

**Bavenite** is a zeolite, recently described, chemically related to gismondite. The formula is $Ca_3Al_2(SiO_3)_6 + H_2O$. It is in radial fibrous aggregates elongated || $c$ and flattened parallel 100. Cleavage easy || 010. H. = 5.5. G. = 2.72. The acute bisectrix Z is normal to 010; $X \wedge c = 2^\circ \pm$. $2E = 78^\circ 30'$. ($2V = 47^\circ 13'$). $n_m = 1.58$. Found in druses in pegmatite.

DIAG. The exterior form distinguishes gismondite from all other zeolites. The twinning is also notable.

## LAUMONTITE.

MONOCLINIC $a:b:c :: 1.1451 : 1 : 0.5906$ $CaAl_2Si_4O_{12} + 4H_2O$
$\beta = 68^\circ 46'$

PHYS. CHAR. Crystals commonly prismatic, more or less vertically elongated and terminated by 001, $\bar{2}01$, 111, etc. Faces of the prism zone are vertically striated. Twinning plane 100. Also columnar, radiating. Cleavage perfect || 010 and 110, difficult || 100 and $\bar{2}01$. Laumontite sometimes becomes opaque and disintegrates to a powder on exposure to air. H. = 3.5-4. Very fragile. G. = 2.25-2.36. Before the blowpipe swells and fuses at about 3. to a white enamel. Gelatinizes with HCl.

OPT. PROP. The plane of the optic axes is parallel to 010; the negative acute bisectrix makes an angle of 60° to 65° with the vertical axis in the obtuse angle $\beta$, and the elongation is therefore positive, with a maximum extinction angle of 25° to 30°. The angle of the optic axes is moderate; the axial dispersion is very distinct, $\rho < v$. Inclined dispersion very weak. Refringence low; birefringence stronger than in quartz.

$$(-)\ 2E = 52^\circ 24' \text{ (red) } 56^\circ 15' \text{ (blue)}$$
$$n_g = 1.525 \quad n_m = 1.524 \quad n_p = 1.513$$
$$n_g - n_p = 0.012$$

Color white, colorless, yellowish, grayish, etc. Colorless in section.

ALTER. Laumontite easily loses one molecule of water and becomes opaque and pulverulent; another molecule is driven off at low heat.

OCCUR. Found in veins in crystalline schists, clay slate, etc.; also in cavities in igneous rocks.

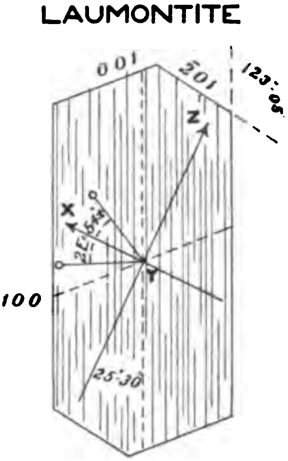


Figure 216.
Optical orientation of laumontite.

DIAG. The perfect cleavage in the three directions is quite characteristic. Further, the mineral has positive elongation with a large extinction angle, and stronger birefringence than phillipsite.

## CHABAZITE.

PSEUDOHEXAGONAL $c = 1.086$ $(Ca,Na_2)Al_2(SiO_3)_4 + 6H_2O$

PHYS. CHAR. Crystals often simple rhombohedrons, resembling a cube, since $10\bar{1}1 \wedge \bar{1}101 = 85° 14'$; sometimes more complex forms; rarely flattened || 0001. Twinning plane commonly 0001, usually in penetration. Cleavage distinct || $10\bar{1}1$. H. = 4-5. G. = 2.08-2.16. Before the blowpipe intumesces and fuses to dark blebby glass. Decomposed by HCl with separation of slimy silica. The composition is somewhat variable.

OPT. PROP. Chabazite is considered probably triclinic by Becke and Rinne, and the pseudorhombohedral cleavage is considered to be cleavage parallel to 001, 010, and 100. The apparent symmetry is hexagonal and many crystals are optically uniaxial, or very nearly so. Others show distinct biaxial figures; these are commonly divided into sectors of varying extinction. The optic angle is variable, but usually small. The sign is negative; or, positive, perhaps when containing more water. Considerable heating changes both varieties to crystals with strong positive birefringence. In natural crystals the refringence is low and the birefringence very weak.

$$(\pm)\ 2V = 0°\text{-}?°$$
$$n_g \doteq 1.488 \quad n_m = ? \quad n_p = 1.485$$
$$n_g - n_p = 0.003$$

Color white, colorless, pink. Luster vitreous. Colorless in section.

OCCUR. Chabazite occurs in cavities in volcanic rocks often associated with phillipsite; it is found in fractures in crystalline limestone with stilbite, laumontite, thomsonite, etc.; in crystalline schists it occurs with stilbite, heulandite, laumontite, analcite, etc.; it is quite abundant in certain hot springs, where it is of recent origin.

DIAG. The exterior forms are like those of gmelinite from which chabazite differs in cleavage and in composition; it differs from other zeolites in being of variable sign, nearly or quite uniaxial, and of very weak birefringence.

## GMELINITE.

PSEUDOHEXAGONAL $c = 0.7345$ $(Na_2,Ca)Al_2(SiO_3)_4 + 6H_2O$

PHYS. CHAR. Crystals usually apparently hexagonal or rhombohedral; prismatic faces often horizontally striated. Penetration twins frequent. Twinning plane 0001, or $30\bar{3}2$, which corresponds to twinning parallel to $10\bar{1}1$ in chabazite. Cleavage easy || $10\bar{1}0$, sometimes distinct || 0001. H. = 4.5. G. = 2.04-2.17. Before the blowpipe fuses at about 3 to a white enamel. Decomposed by HCl with separation of silica. The composition is somewhat variable, but similar to chabazite with more sodium.

OPT. PROP. Similar to chabazite in being optically positive or negative with frequent biaxial figures of small optic angle; in such cases the section has areas of varying orientation. The refringence is low and birefringence weak, but somewhat variable.

$$(\pm)\ 2V = \text{small}$$
$$n_g = 1.4646\text{-}1.4803 \quad n_p = 1.4637\text{-}1.4785$$
$$n_g - n_p = 0.0009\text{-}0.0086$$

Colorless, white, yellowish, greenish, pinkish. Colorless in section.

Occur. Gmelinite is found in cavities in igneous and schistose rocks.

Diag. Gmelinite differs from chabazite in its cleavage and composition; it differs from other zeolites in being of apparent hexagonal form, nearly or quite uniaxial, and of variable sign.

## ANALCITE.

Pseudoisometric $NaAl(SiO_3)_2 + H_2O$

Phys. Char. Usually in trapezohedrons; also in modified cubes, or in more complex forms. Also granular or compact. Complex penetration twinning very common. Cleavage || 001 in traces only. H. = 5.-5.5. G. = 2.22-2.29. Before the blowpipe fuses to colorless glass. Gelatinizes with HCl.

Opt. Prop. Usually isotropic in thin section, but weak birefringence is often found, which disappears upon heating to 130° C., at which temperature analcite becomes strictly isometric. When anisotropic analcite has very weak birefringence and a very small optic angle about a negative bisectrix.

$$(-)\ 2V = \text{very small}$$
$$n = 1.487$$
$$n_g - n_p = 0.001$$

Colorless, white, grayish, greenish, etc. Colorless in thin section.

Occur. Analcite is usually a secondary mineral like the other zeolites, and it is known to be an alteration product of nepheline, leucite, and sodalite, and also to occur in cavities, etc. closely associated with other zeolites. But it also seems to be formed directly from the cooling magma in certain basalts, and other volcanic rocks.

Diag. Analcite is characterized by very low refringence and nearly or completely isotropic character. It differs from sodalite by the absence of color often present in the latter, and by the cleavage. It differs from leucite by the absence of regularly arranged inclusions common in the latter, by the cleavage when visible, and by the composition. Analcite has higher refringence than opal, and distinctly lower relief than rock glass; from both of these its cleavage also distinguishes it. But the chemical tests are sometimes necessary to identify it certainly.

## EDINGTONITE.

ORTHORHOMBIC $a:b:c::0.987:1:0.673$ $BaAl_2Si_3O_{10} + 3H_2O$

PHYS. CHAR. Crystals minute and apparently tetragonal; also massive. Cleavage perfect || 110. H. = 4-4.5. G. = 2.69-2.71. Fusible at 5. Gelatinizes with HCl.

OPT. PROP. The optic plane is parallel to 010; the acute bisectrix X is normal to 001. Dispersion $\rho < v$ weak. Color white, grayish, pink. Luster vitreous.

$$(-)\ 2E = 87° 17' \ (2V = 52° 55')$$
$$n_g = 1.5540 \quad n_m = 1.5492 \quad n_p = 1.5382$$
$$n_g - n_p \pm 0.0158$$

OCCUR. Found with other zeolites. Very rare.

## NATROLITE.

ORTH. $a:b:c::0.9785:1:0.3536$ $Na_2Al_2Si_3O_{10} + 2H_2O$

PHYS. CHAR. Crystals nearly always prismatic, much elongated, commonly acicular to fibrous. The prismatic angle is near 90° producing pseudotetragonal forms. Faces of prism zone vertically striated. Often in interlacing groups or divergent. Very rarely in crystals elongated || *b*. Brögger regards some natrolite as monoclinic, with $\beta = 89° 55'$. Twinning on 301 very rare, in penetration crosses, nearly rectangular. Microscopic twinning on 110; perhaps also 100. Cleavage perfect || 110; imperfect cleavage or parting || 010. H. = 5.-5.5. G. = 2.2-2.27. Fusible quietly at 2. to colorless glass. Gelatinizes with HCl.

OPT. PROP. The plane of the optic axes is parallel to 010; the positive acute bisectrix is perpendicular to 001. The angle of the optic axes is large. The refringence is very low, and the birefringence slightly stronger than that of quartz.

$$(+)\ 2V = 60°\text{-}62° \ (2E = 94° \pm)$$
$$n_g = 1.485\text{-}1.493$$
$$n_m = 1.476\text{-}1.482$$
$$n_p = 1.473\text{-}1.480$$
$$n_g - n_p = 0.012\text{-}0.013$$

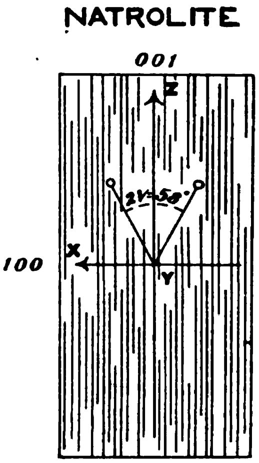


Figure 217.
Optical orientation of natrolite.

Color white, colorless, grayish, yellowish. Colorless in section.

Twinning on 110 may be so regular and so fine as to lead to an apparent uniaxial condition. Heat modifies natrolite, and it becomes monoclinic.

OCCUR. Natrolite is found in basic igneous rocks, such as basalts, occurring as an amygdaloidal filling. It also occurs as an alteration product of nepheline, sodalite, and plagioclase in syenite and more basic rocks.

DIAG. Natrolite is distinguished from thomsonite by much weaker birefringence and the positive sign of the elongation; it is distinguished from scolecite and mesolite by having parallel extinction and positive elongation; it differs from epistilbite and laumontite by having parallel extinction and a positive bisectrix.

## SCOLECITE.

MONOCLINIC $a:b:c::0.976:1:0.339$ $CaAl_2Si_3O_{10}+3H_2O$

$\beta = 88° 50'$

PHYS. CHAR. Crystals slender, prismatic, vertically striated; commonly in fibrous masses, divergent or radiated, like natrolite. Twinning plane commonly 100; rarely 110. Cleavage nearly perfect || 110. H. = 5.-5.5. G. = 2.16-2.4. Before the blowpipe sometimes curls into worm-like forms (whence the name), and fuses at about 2 to a white blebby enamel. Gelatinizes with acids.

OPT. PROP. The plane of the optic axes is perpendicular to 010; the negative acute bisectrix makes an angle of about 15° with $c$ in the obtuse angle $\beta$. The refringence is low, and the birefringence weak. The dispersion of the axes is distinct with $\rho < v$.

$$(-)\ 2V = 36° 26' \quad (2E = 36° 26' - 55° 44')$$

$$n_g = 1.5194 \quad n_m = 1.5187 \quad n_p = 1.5122$$

$$n_g - n_p = 0.0072\text{-}0.0083$$

Colorless or white.

OCCUR. Scolecite is found in cavities in basic igneous rocks, and also in crystalline schists, and in limestone modified by igneous contact.

DIAG. Scolecite is distinguished from natrolite by its inclined extinction and negative elongation; from thomsonite by its weaker birefringence, inclined extinction, and negative elongation; from mesolite by its greater angle of extinction and its negative

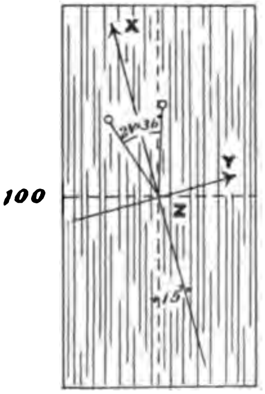


Figure 218.
Optical orientation of scolecite.

elongation; from stilbite by its greater angle of extinction as measured on the elongation.

## MESOLITE.

TRICLINIC Axial ratio unknown $m\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} + 2\text{H}_2\text{O} + n\text{CaAl}_2\text{Si}_3\text{O}_{10} + 3\text{H}_2\text{O}$

PHYS. CHAR. Crystal form very similar to that of scolecite; commonly finely fibrous in divergent groups. Twinning on 100 constant, but only visible microscopically. Cleavage perfect || 110 and 1$\bar{1}$0. H. = 5. G. = 2.2-2.4. Before the blowpipe swells into vermicular forms, and fuses easily to a blebby enamel. Gelatinizes with HCl.

OPT. PROP. The plane of the optic axes is nearly perpendicular to 010; the positive acute bisectrix is sensibly perpendicular to 100. The extinction angle in a section parallel to 010 is about 5° to 6°; it is the same in a section parallel to 100. The refringence is low, and the birefringence very weak. Twinning on a microscopic scale is constant. The angle of the optic axes is large; the axial dispersion is very marked with $\rho > v$.

$$(+)\ 2V = \text{very large.}$$

$$n_g - n_p = 0.004 \pm$$

Colorless, white, grayish or yellowish. Colorless in section.

OCCUR. Mesolite occurs in cavities in basic igneous rocks.

DIAG. Mesolite is distinguished from both natrolite and scolecite by the variable sign of the elongation. From other zeolites this character, the fibrous habit, and the small extinction angle, serve as distinctions.

## PSEUDOMESOLITE.

TRICLINIC? Axial ratio unknown $m\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} + 2\text{H}_2\text{O} + n\text{CaAl}_2\text{Si}_3\text{O}_{10} + 3\text{H}_2\text{O}$

PHYS. CHAR. Found in fibrous, radiating spherulitic masses with few interlacing fibers. Form similar to that of mesolite, but twinning unknown. Distinct cleavage in two directions, considered 110 and 1$\bar{1}$0 by analogy with mesolite. H. = 4.5-5. G. = 2.215. Fuses at about 2 without noticeable change of volume to a white porcelain. Gelatinizes with acids only.

OPT. PROP. The positive acute bisectrix makes an angle of about 20° with the axis of elongation *c*; the axes X and Y are in such positions as to produce extinction sensibly parallel with the diagonals of the rhombs formed by the prism faces in cross sections. The refringence is very low, and the birefringence very weak. The angle of the optic axes is quite small.

$$(+)\ 2V = \text{very small}$$

$$n_g - n_p = 0.002 \text{ about}$$

Color porcelain white, but often stained pinkish or greenish. Colorless in thin section.

OCCUR. Found in cavities in plagioclasite of Carlton peak, Minnesota. Rare.

Diag. Pseudomesolite may be distinguished from mesolite by the sign of the elongation, the large extinction angle, the very small optic angle; from natrolite and thomsonite by the extinction angle and the small optic angle; from scolecite by the sign of the elongation and of the acute bisectrix, and by the weaker birefringence; from stilbite by the small optic angle, and by the sign of the elongation and of the acute bisectrix.

## THOMSONITE.

Orth. $a:b:c::0.993:1:1.006$ $(Ca,Na_2)Al_2(SiO_4)_2+2\frac{1}{2}H_2O$

Phys. Char. Euhedral crystals rare; habit prismatic, usually much elongated, prism faces vertically striated. Commonly lamellar || 010, sometimes fibrous to columnar, often radiated. Cleavage perfect || 010, imperfect || 100, in traces || 001. H. = 5.-5.5. G. = 2.3-2.4. Fuses at 2 with intumescence to a white enamel. Gelatinizes with HCl.

Opt. Prop. The plane of the optic axes is parallel to 001; the positive acute bisectrix is normal to 010. The refringence is lower than that of orthoclase, but the birefringence the strongest known in the zeolite group. The angle of the optic axes is large; the dispersion is marked, with $\rho>v$.

$$(+)\ 2V=54^\circ\pm$$
$$(2E_r=85^\circ\ 45'\quad 2E_v=88^\circ\ 36')$$
$$n_g=1.525\quad n_m=1.503\quad n_p=1.498$$
$$n_g-n_p=0.027$$

Colorless, white, yellowish, pink. Colorless in section.

Occur. Thomsonite is always closely associated with other zeolites or with prehnite. It is found in cavities in igneous rocks and in crystalline schists. It also occurs in crystalline limestone near igneous contacts. It results from the decomposition of plagioclase or of nephelite.

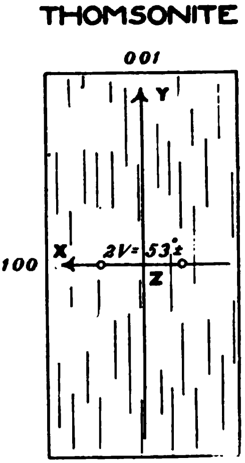


Figure 219.
Optical orientation of thomsonite.

**Lintonite** can not be distinguished chemically from thomsonite and mesolite and pseudomesolite, but it differs from them in its optical characters, since it has negative elongation and an extinction angle of about 19°; its refringence is less than that of thomsonite, and its birefringence is much stronger than that of mesolite and pseudomesolite (about 0.017), though less than that of thomsonite; the optic angle is very small about the positive acute bisectrix; it has a specific gravity of 2.37, and occurs in very short fibers of somewhat irregular form in cavities in basic igneous rocks in northern Minnesota.

**Jacksonite** is very similar to lintonite, but contains less water; it has positive elongation with a very small extinction angle; its specific gravity is reported to be 2.68-2.88, and its hardness 6. It is found in the same region as lintonite.

**Chlorastrolite** is another mineral resembling thomsonite in composition. Optically it has elongation of variable sign, and the extinction angle reaches about 20°. It has distinct pleochroism from colorless to light green. The hardness is 5.5 and the specific gravity is 3.15. The only analysis shows less water and more iron than are found in thomsonite. It is found in northern Minnesota.

DIAG. Thomsonite is readily distingushed from all other zeolites by its stronger birefringence; it differs from others also in having elongation of variable sign, and parallel extinction.

## HYDRONEPHELITE.

HEXAGONAL · Axial ratio unknown $HNa_2Al_3(SiO_4)_3 + 3H_2O$

PHYS. CHAR. Commonly apparently massive, compact, microscopically somewhat fibrous and scaly. Indistinct prismatic cleavage. H. = 4.5-6. G. = 2.26. Easily fusible to a white enamel. Gelatinizes with HCl.

OPT. PROP. Uniaxial and positive. The refringence is low and the birefringence weak.

$$n = 1.49$$

$$n_g - n_p = 0.010 \text{ about}$$

Color white, pink, gray to grayish black. Colorless in thin section, but sometimes clouded by dark dusty particles.

OCCUR. Hydronephelite is often an alteration product of nephelite (whence the name); it is also derived from sodalite, and is therefore commonly found in nepheline syenite or related rocks. It is frequently associated with thomsonite, diaspore, etc.

**Ranite** is a variety containing about 5% CaO; it occurs from the alteration of nephelite in syenite of Norway. Rare.

DIAG. Hydronephelite is characterized by its positive uniaxial character; it is distinguished from other uniaxial zeolites (and from natrolite, which sometimes forms uniaxial groups by twinning) by its stronger birefringence.

**ZEUNERITE,** see torbernite.

**ZINCITE.**

Hexagonal $c = 1.622$ $ZnO$

Phys. Char. Crystals rare, hemimorphic. Usually foliated massive, or granular. Cleavage perfect || 0001, sometimes distinct || $10\bar{1}0$. H. = 4.-4.5. G. = 5.43-5.7. Infusible. Soluble in acids.

Opt. Prop. Uniaxial and positive. Refringence very high, $n = 2.$ approximately; $n_g - n_p = 0.021$ approximately. Color deep red; rarely orange yellow. Streak orange yellow. Luster subadamantine.

Alter. Atmospheric alteration produces smithsonite.

Occur. Found with franklinite and willemite in New Jersey. Rare.

**ZINNWALDITE,** see mica group. **ZIRCON,** see rutile group. **ZOISITE,** see epidote group.

Moissanite and the following new minerals are not included in Part III, as information concerning them was not available when the tables were electrotyped.

**HILLEBRANDITE.**[1]

Orthorhombic Axial ratio unknown $(CaOH)_2SiO_3$

Phys. Char. Fibrous, often in radial spherulites. Cleavage prismatic. H. = 5.5. G. = 2.692. Fusible difficultly to colorless glass. Soluble in HCl.

Opt. Prop. The position of the optic plane is variable or uncertain, apparently parallel with 010. The obtuse bisectrix Z is always parallel with *c*. The refringence is moderate, and birefringence weak. The optic angle ($2E$) is possibly between 60° and 80°; axial dispersion $\rho < v$, is very strong, giving abnormal interference colors.

$$(-)\quad 2E = 70^\circ\ ?$$

$$n_g = 1.612 \pm 0.003 \quad n_m = ? \quad n_p = 1.605 \pm 0.005$$

Color porcelain white or greenish. Colorless in section.

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[1] F. E. Wright: *Amer. Jour. Sc.* XXVI. 1908. p.551.

OCCUR. Found with carbonate, yellow garnet, and wollastonite in a contact zone in Mexico. Very rare.

DIAG. Hillebrandite is characterized by its moderate relief, weak birefringence, moderate optic angle, and strong dispersion producing abnormal interference tints.

## SPURRITE.[1]

MONOCLINIC? Axial ratio unknown $CaCO_3 \cdot 2CaSiO_4$

PHYS. CHAR. Granular masses with two cleavages, one good || 001 and one poor || 100 (?). Cleavage angle 79°. Twinning on 001, and an orthodome making an angle of about 57° with 001, the latter polysynthetic. H. = 5. G. = 3.014. Infusible. Soluble in HCl with effervescence and gelatinization. Etching figures suggest triclinic symmetry.

OPT. PROP. The optic plane and acute bisectrix X are normal to 010, and Z is sensibly parallel with $a$. The refringence is high and the birefringence strong, while the optic angle is moderate. Distinct crossed dispersion, with $\rho > v$ weak.

$$(-) \quad 2E = 70° \quad (2V = 39\tfrac{1}{2}°)$$
$$n_g = 1.679 \quad n_m = 1.674 \quad n_p = 1.640$$
$$n_g - n_p = 0.039$$

Color pale gray, bluish, yellowish. Colorless in section.

ALTER. Alteration to carbonate in fine aggregates occurs first along cleavage planes and fractures.

OCCUR. Found with yellow garnet, calcite, and gehlenite in a zone of contact metamorphism in Mexico. Very rare.

DIAG. Spurrite is recognized in thin section by its strong birefringence, imperfect cleavage, moderate optic angle of negative sign, and high relief.

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[1] F. E. Wright: *Amer. Jour. Sc.* XXVI. 1908. p. 547.

# PART III.

# TABLES

## TABLES FOR THE DETERMINATION OF MINERALS MICROSCOPICALLY.

In the table which follows minerals are primarily classed as:— A. Opaque. B. Isotropic, C.I. Anisotropic, uniaxial, C.II. Anistropic, biaxial, and then are subdivided on the basis of their refringence. In order to use this property of refringence with more precision the following scale has been adopted:—

*Scale of refringence.*

1. Fluorite. Very low. $n < 1.52$.
   $<$ Limit orthoclase $n_m = 1.523\text{-}1.526$
2. Quartz. Low. $n > 1.52 < 1.59$.
   $<$ Limit muscovite $n_m = 1.587\text{-}1.605$
3. Common hornblende. Moderate. $n > 1.59 < 1.66$.
   $<$ Limit enstatite $n_p = 1.656\text{-}1.665$
4. Augite. High. $n > 1.66 < 1.75$
   $<$ Limit staurolite $n_g = 1.746\text{-}1.75+$
5. Zircon. Very high. $n > 1.75$.

Whenever a direct comparison by the Becke method can be made between the indices of the unknown mineral and those of the common minerals thus selected as limits an absolutely accurate classification is possible even though the differences in the indices are very slight. For this purpose not only are the minerals named above available, but other common minerals are very near the limits selected. Thus, in addition to orthoclase we have microcline with $n_m = 1.522\text{-}1.526$ and anorthoclase with $n_p = 1.521\text{-}1.525$; with muscovite we have brown and green biotite for which $n_g = 1.579\text{-}1.603$ (omitting black varieties), clinochlore with $n_m = 1.586\text{-}1.588$, and talc with $n_m = 1.589$; in place of enstatite we may use bronzite with $n_m = 1.668$, or pure calcite, with $n_g = 1.6585$, or pure diopside with $n_p = 1.671\text{-}1.677$, or the common iron-poor positive varieties of olivine which have $n_p = 1.654\text{-}1.672$; finally, instead of staurolite we may use grossularite garnet with $n = 1.744\text{-}1.757$, or epidote (rich in iron) with $n_m = 1.754$.

Further, the comparison by the Becke method of the indices of an unknown mineral with those of any known mineral with which it may be in contact will always give at least one limit, and in connection with the visible amount of relief this may be sufficient.

But it is believed that minerals can be accurately classed in this scale of refringence in nearly all cases simply by comparing the relief of the unknown mineral with that of the various type minerals selected, or with that of the minerals selected as limits. For this purpose the type minerals or the limiting minerals may be sought in sections already available, or, more conveniently, they may be all mounted with the proper orientation to show the indices desired in a single slide. Such a slide would then serve as a standard for comparisons.

In view of the fact that an unknown mineral is usually cut in an indefinite direction, and that therefore its relief may correspond to any of its indices, or to any intermediate values, all minerals are entered in the table, not on the basis of the mean index of refraction, but in as many places as necessary to express the whole range of the indices of refraction.

Further subdivisions in the first table are based on the birefringence. For convenience in the use of this character the following scale has been employed.

*Scale of birefringence.*

| | | | | | Interference colors in sections 0.03 mm. thick. |
|---|---|---|---|---|---|
| 1. | Leucite. | Very weak. | $n_g - n_p < 0.0035$. | Dark grays | First Order |
| 2. | Orthoclase. | Weak. | $n_g - n_p > 0.0035 < 0.0095$. | Gray and white | |
| 3. | Hypersthene. | Moderate. | $n_g - n_p > 0.0095 < 0.0185$. | Yellow and red | |
| 4. | Augite. | Rather strong. | $n_g - n_p > 0.0185 < 0.0275$. | Blue and green | Second Order |
| 5. | Diopside. | Strong. | $n_g - n_p > 0.0275 < 0.0355$. | Yellow and red | |
| 6. | Muscovite. | Strong. | $n_g - n_p > 0.0355 < 0.0445$. | Blue and green | Third Order |
| 7. | Acmite. | Very strong. | $n_g - n_p > 0.0445 < 0.0565$. | Yellow and red | |
| 8. | Titanite. | Extreme. | $n_g - n_p > 0.0565$. | Greenish and violet grays | Fourth Order Up |

Since all anisotropic minerals may be cut so as to give the lowest interference colors, only the ***maximum*** birefringence is a property of determinative value, and it is necessary to assume that the maximum interference color can be obtained from the given unknown mineral. But in the case of minerals whose maximum birefringence varies with variation in the composition, as in hornblende, the names are entered in the tabulation in as many places as necessary to express such variations.

Further subdivisions in the groups of minerals having similar refringence and birefringence are based on characters often more difficult to determine, or subject to exceptions. Thus, each group is first divided into positive minerals and negative minerals, and then each division is classified according to the crystal system, beginning with the system of greater symmetry; finally, in the small groups thus established the minerals are classified according as they have no elongation, positive elongation, plus or minus elongation, or negative elongation.

Other characters expressed in the table, but not used in the classification, include the optic orientation, extinction angles, color, pleochroism, cleavage, optic angle, dispersion, and chemical composition.

The use of the table may be illustrated by the following examples. In section No. H 331 a colorless mineral occurs which is anisotropic with pale yellow of the first order as the maximum interference color. The thickness of the section is about 0.025 mm., as determined from the birefringence of known minerals in the slide; the birefringence of the unknown mineral is therefore about 0.013, or moderate. The mineral has no relief; sections which remain dark on rotation between crossed nicols show that it is uniaxial and negative. By reference to the general classification on page 418 these characters are ample to indicate that the mineral belongs in group 2c on page 433. In this group the only negative mineral with a birefringence of 0.013 is dipyre. This determination is confirmed by the presence of cleavage in two rectangular directions in basal sections and cleavage parallel to the optic axis in vertical sections.

As an illustration of a determination depending upon more characters, and somewhat more complicated, the following may serve. A good thin section of a peculiar dark grayish green massive rock from Montana contains numerous sections of a strongly pleochroic mineral (green and yellow), with high relief like that of augite; its highest interference color is yellow of the second order, which indicates strong birefringence. If it were impossible to obtain characteristic interference figures to determine whether the mineral is uniaxial or biaxial, by reference to the general classification on page 418 it will be seen that since the mineral is anisotropic with high refringence and strong birefringence it must be found either on page 439 under group 4e (if uniaxial), or on page 460 under group 4e (if biaxial.). The mineral has good cleavage in two directions nearly at right angles, therefore it is neither tourmaline nor hematolite (see page 439) and must belong on page 460. The mineral is elongated parallel to the intersection of the cleavages, and one infers that the cleavages are prismatic and the elongation parallel to *c*. The extinction in vertical sections varies from 0° to about 30°; therefore the mineral is monoclinic. The direction of elongation is always negative and the angle between Z (or Y) and *c* is about 60°. The only mineral with this extinction angle in the group 4e (page 460) is ægirinaugite. The pleochroic formula confirms this determination, as well as the fact that the mineral is actually biaxial and positive. In the preceding description the last named characters were not used in order to illustrate the use of the tables when certain characters could not be determined.

# GENERAL CLASSIFICATION OF MINERALS.

Success in using the following analytical tables depends wholly upon accuracy in assigning a mineral to the group in which it belongs; therefore the following general classification should be used with the utmost care.

| | Page. | |
|---|---|---|
| A. Opaque. | | |
| I. Always opaque in thin section | 420 | |
| II. Subtranslucent to opaque in thin section | 422 | |
| B. Isotropic. | | |
| I. Amorphous | 424 | |
| II. Isometric. | | |
| 1. Refringence very low $< 1.52$ | 425 | |
| 2. Refringence low $> 1.52 < 1.59$ | 426 | |
| 3. Refringence moderate $> 1.59 < 1.66$ | 426 | |
| 4. Refringence high $> 1.66 < 1.75$ | 426 | |
| 5. Refringence very high $> 1.75$ | 427 | |
| C. Anisotropic. | | |
| I. Uniaxial and II. Biaxial. | **Uniaxial** | **Biaxial** |
| o. Indices unknown | | 446 |
| 1. Refringence very low $< 1.52$ | | |
| a. Birefringence unknown | | 447 |
| a. Birefringence very weak $< 0.0035$ | 430 | 448 |
| b. Birefringence weak $> 0.0035 < 0.0095$ | 430 | 448 |
| c. Birefringence moderate $> 0.0095 < 0.0185$ | 431 | 448 |
| d. Birefringence rather strong $> 0.0185 < 0.0275$ | 431 | 449 |
| e. Birefringence strong $> 0.0275 < 0.0355$ | 431 | 449 |
| f. Birefringence strong $> 0.0355 < 0.0445$ | 431 | ... |
| g. Birefringence extreme $> 0.0565$ | 432 | 449 |
| 2. Refringence low $> 1.52 < 1.59$. | | |
| a. Birefringence unknown | | 450 |
| a. Birefringence very weak $< 0.0035$ | 432 | 450 |
| b. Birefringence weak $> 0.0035 < 0.0095$ | 432 | 450 |
| c. Birefringence moderate $> 0.0095 < 0.0185$ | 433 | 451 |
| d. Birefringence rather strong $> 0.0185 < 0.0275$ | 433 | 452 |
| e. Birefringence strong $> 0.0275 < 0.0355$ | 433 | 452 |
| f. Birefringence strong $> 0.0355 < 0.0445$ | 434 | 453 |
| g. Birefringence very strong $> 0.0445 < 0.0565$ | 434 | 453 |
| h. Birefringence extreme $> 0.0565$ | 435 | 453 |

## GENERAL CLASSIFICATION OF MINERALS—(Cont.).

| | | Uniaxial | Biaxial |
|---|---|---|---|
| C. | Anisotropic. (Cont.) | | |
| I. | Uniaxial and II. Biaxial. (Cont.) | | |
| 3. | Refringence moderate $> 1.59 < 1.66$ | | |
| α. | Birefringence unknown | | 454 |
| a. | Birefringence very weak $< 0.0035$ | 435 | 454 |
| b. | Birefringence weak $> 0.0035 < 0.0095$ | 436 | 454 |
| c. | Birefringence moderate $> 0.0095 < 0.0185$ | 436 | 454 |
| d. | Birefringence rather strong $> 0.0185 < 0.0275$ | 437 | 455 |
| e. | Birefringence strong $> 0.0275 < 0.0355$ | 437 | 456 |
| f. | Birefringence strong $> 0.0355 < 0.0445$ | 437 | 456 |
| g. | Birefringence very strong $> 0.0445 < 0.0565$ | 438 | 457 |
| h. | Birefringence extreme $> 0.0565$ | 438 | 457 |
| 4. | Refringence high $> 1.66 < 1.75$. | | |
| α. | Birefringence unknown | | 457 |
| a. | Birefringence very weak $> 0.0035$ | 439 | 458 |
| b. | Birefringence weak $> 0.0035 < 0.0095$ | 439 | 458 |
| c. | Birefringence moderate $> 0.0095 < 0.0185$ | 439 | 458 |
| d. | Birefringence rather strong $> 0.0185 < 0.0275$ | 439 | 459 |
| e. | Birefringence strong $> 0.0275 < 0.0355$ | 439 | 460 |
| f. | Birefringence strong $> 0.0355 < 0.0445$ | 440 | 460 |
| g. | Birefringence very strong $> 0.0445 < 0.0565$ | 440 | 461 |
| h. | Birefringence extreme $> 0.0565$ | 440 | 461 |
| 5. | Refringence very high $> 1.75$. | | |
| α. | Birefringence unknown | | 462 |
| a. | Birefringence very weak $< 0.0035$ | 441 | 462 |
| b. | Birefringence weak $> 0.0035 < 0.0095$ | 441 | 462 |
| c. | Birefringence moderate $> 0.0095 < 0.0185$ | 442 | 462 |
| d. | Birefringence rather strong $> 0.0185 < 0.0275$ | 442 | 463 |
| e. | Birefringence strong $> 0.0275 < 0.0355$ | 442 | 463 |
| f | Birefringence strong $> 0.0355 < 0.0445$ | 443 | 463 |
| g. | Birefringence very strong $> 0.0445 < 0.0565$ | 443 | 463 |
| h. | Birefringence extreme $> 0.0565$ | 444 | 464 |

## A. Opaque Minerals

I. Always opaque in thin section.

| COLOR IN REFLECTED LIGHT | LUSTER | CRYST. SYST. | CLEAVAGE | H. | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|
| Bluish black | Metallic | Isom. | Parting ‖ 111 | 5.5-6.5 | **Magnetite** | $FeFe_2O_4$ | Magnetic. Brown in very thin flakes |
| | Metallic | Isom. | Parting ‖ 111 | 6.-6.5 | Magnesioferrite | $MgFe_2O_4$ | Magnetic. Rare |
| | Subm. | Rhom. | | 5.-6. | **Ilmenite** | $Fe(Ti,Fe)O_3$ | Clove brown in very flakes |
| Iron black to steel gray<br>See also A II below | Metallic | Isom. | Parting ‖ 111 | 5.5-6.5 | Franklinite | $(Fe,Zn,Mn)_3O_4$ | Streak reddish brown to black |
| | Metallic | Isom. | Perf. ‖ 100 | 4.-5. | Iron | Fe | Magnetic |
| | Subm. | Isom. | ‖ 100 | 5.-6. | Dysanalite | $CaTiO_3 \cdot FeNb_2O_6$ | Cubes |
| | Met. to dull | Tetr. | Perf. ‖ 110 | 6.-6.5 | Polianite (Pyrolusite) | $MnO_2$ | Streak black |
| | Metallic to dull | Rhom. | Perf. ‖ 0001 | 1.-2. | Graphite | C | Laminæ flexible |
| Lead gray | Metallic | Isom. | Perf. ‖ 100 | 2.5 | **Galena** | PbS | Cubes or octahedrons |
| | Metallic | Isom. | | 2.-2.5 | Argentite | $Ag_2S$ | Sectile |
| | Metallic | Hex.? | Perf. ‖ 0001 | 1.-1.5 | Molybdenite | $MoS_2$ | Laminæ flexible<br>Sectile |
| | Metallic | Orth. | | 2.5-3. | Chalcocite | $Cu_2S$ | |

## A. Opaque Minerals (Cont.)

I. **Always opaque in thin section. (Cont.)**

| COLOR IN REFLECTED LIGHT | LUSTER | CRYST. SYST. | CLEAVAGE | H. | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|
| Silver or tin white to steel gray | Metallic | Isom. | | 2.5-3. | Silver | Ag | Malleable |
| | Metallic | Isom. | Dist. ‖ 111 | 5.5-6. | Chloanthite | $NiAs_2$ | Streak grayish black |
| | Metallic | Isom. | Dist. ‖ 111 | 5.5-6. | Smaltite | $CoAs_2$ | Streak grayish black |
| | Metallic | Orth. | Dist. ‖ 110 | 5.5-6. | Arsenopyrite | FeAsS | Streak grayish black |
| Silver white (reddish) | Metallic | Isom. | Dist. ‖ 100 | 5.5 | Cobaltite | CoAsS | Streak grayish black |
| Copper red | Metallic | Isom. | | 2.5-3. | Copper | Cu | Malleable |
| Pale copper red | Metallic | Hex. | | 5.-5.5 | Niccolite | NiAs | Streak pale brownish black |
| Brownish copper red | Metallic | Isom. | | 3. | Bornite | $Cu_3FeS_3$ | Tarnishes quickly |
| Violet copper red | Metallic | Hex. | | 5.5 | Breithauptite | NiSb | Streak reddish brown |
| Reddish bronze yellow | Metallic | Hex. | Poor ‖ 0001 | 3.5-4.5 | **Pyrrhotite** | $Fe_{11}S_{12}$ | Magnetic |
| Pale bronze yellow | Metallic | Orth. | Poor ‖ 110 | 6.-6.5 | Marcasite | $FeS_2$ | Oxidizes rapidly by weathering |
| Pale brass yellow | Metallic | Isom. | | 6.-6.5 | **Pyrite** | $FeS_2$ | Cubes, pyritohedrons, octahedrons |

## A. Opaque Minerals (Cont.)

I. Always opaque in thin section. (Cont.)

| COLOR IN REFLECTED LIGHT | LUSTER | CRYST. SYST. | CLEAVAGE | H. | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|
| Brass yellow | Metallic | Tetr. | Poor ‖ 201 and 001 | 3.5-4. | **Chalcopyrite** | $CuFeS_2$ | Streak greenish black |
|  | Metallic | Rhom. | Perf. rhom. | 3.-3.5 | Millerite | $NiS$ | Usually capillary |
| Gold yellow | Metallic | Isom. |  | 2.5-3. | Gold | $Au$ | Malleable |
| Indigo blue | Subm. | Hex. | Perf. ‖ 0001 | 1.5-2. | Covellite | $CuS$ | Laminæ flexible |

II. Subtranslucent to opaque in thin section.

| COLOR IN TRANSMITTED LIGHT | COLOR IN REFLECTED LIGHT | LUSTER | CRYST. SYST. | CLEAVAGE | H. | NAME | COMP. |
|---|---|---|---|---|---|---|---|
| blood red to black | Blood red | Metallic to dull | Hex. | Parting ‖ 0001 | 5.5-6.5 | **Hematite** | $Fe_2O_3$ |
| Dark red to black | Lead gray | Metallic | Orth. | Perf. ‖ 010 | 2. | Stibnite | $Sb_2S_3$ |
| Cherry red | Gray to black | Metallic | Isom. |  | 3.-4.5 | Tetrahedrite | $Cu_8Sb_2S_7$ |
| Brownish red to black | Dark brown to black | Submet. | Mono. | Perf. ‖ 010 | 5.-5.5 | Wolframite | $FeWO_4$ |
|  | Black | Vitreous | Isom. |  | 7.-7.5 | Schorlomite | $Ca_3Fe_2(Si,Ti)_3O_{12}$ |
| Yellowish brown, red to black | Iron to brownish black | Subm. to met. | Isom. |  | 5 5 | Chromite | $FeCr_2O_4$ |

## A. Opaque Minerals. (Cont.)

### II. Subtarnslucent to opaque in thin section. (Cont.)

| COLOR IN TRANSMITTED LIGHT | COLOR IN REFLECTED LIGHT | LUSTER | CRYST. SYST. | CLEAVAGE | H. | NAME | COMP. |
|---|---|---|---|---|---|---|---|
| Reddish brown to black | Black | Subm. | Orth. | Poor ‖ 100 | 6. | Columbite | $(Fe,Mn)Nb_2O_6$ |
| | Black | Subm. | Tetr. | | 5.-5.5 | Plattnerite | $PbO_2$ |
| Green to black (rarely brown) | Green to yellow | Dull | Amor. | | 5.? | Greenalite | $FeSiO_3+nH_2O$? |
| Leek green to black | Black | Vitreous to dull | Isom. | | 7.5-8. | Hercynite | $FeAl_2O_4$ |

## B. Isotropic Minerals

### I. Amorphous

| COLOR | REFRINGENCE | NAME | COMPOSITION |
|---|---|---|---|
| Colorless | 1.40-1.45 | Opal | $SiO_2+nH_2O$ |
| | 1.48-1.50 | Acid obsidian and residual rock glass | |
| | 1.50-1.51 | Artificial.— Glass from granite | $SiO_2$ 67—72% |
| | 1.52 | " " syenite | " 60% |
| | 1.55 | " " monzonite | " 54% |
| | 1.59 | " " basalt | " 49% |
| | 1.62 | " " gabbro | " 44% |
| | 1.63 | " " harzburgite | " 42% |
| Yellow to colorless | High | Thorite | $ThSiO_4$ (altered) |
| Reddish brown to colorless | 1.82 | Malacon | $ZrSiO_4$ (altered) |
| Bright green | 1.59 | Garnierite | $H_2(Ni,Mg)SiO_4+nH_2O$? |
| Green to black (rarely brown) | ? | Greenalite | $FeSiO_3+nH_2O$? |

## B. Isotropic Minerals. (Cont.)

II. Isometric.

1. Refringence very low <1.52

| COLOR | REFRINGENCE | CLEAVAGE | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|
| Colorless | 1.3325 | ‖ 110 | Cryolithionite | $Na_3Li_3Al_2F_{12}$ | Very rare |
|  | 1.434 | Perf. ‖ 111 | Fluorite | $CaF_2$ | Sometimes violet, reddish, or yellow |
|  | 1.456 |  | Kalinite | $KAl(SO_4)_2+24H_2O$ | Often weakly birefringent |
|  | 1.487 |  | Analcite | $NaAl(SiO_3)_2+H_2O$ | Sometimes weakly birefringent |
|  | 1.490 | Perf. ‖ 100 | Sylvite | $KCl$ | Rarely bluish or pink |
|  | 1.508 |  | Leucite | $KAl(SiO_3)_2$ | Large crystals usually weakly birefringent |
|  | 1.5144 |  | Northrupite | $MgCO_3 \cdot Na_2CO_3 \cdot NaCl$ | Very rare |
| Colorless to blue, green or brown | 1.483-1.486 | Poor ‖ 110 | Sodalite | $Na_4(Al \cdot Cl)Al_2(SiO_4)_3$ | Sometimes weakly birefringent about inclusions |
|  | 1.495 | Poor ‖ 110 | Noselite | $Na_4(Al \cdot NaSO_4)Al_2(SiO_4)_3$ | Sometimes weakly birefringent about inclusions |
|  | 1.496 | Poor ‖ 110 | Haüynite | $(Na_2,Ca)_2(Al \cdot NaSO_4)Al_2(SiO_4)_3$ | Sometimes weakly birefringent about inclusions |
| Blue | 1.5± | Poor ‖ 110 | Lazurite | $Na_4(Al \cdot NaS)Al_2(SiO_4)_3$ | Sometimes weakly birefringent about inclusions |
| Carmine red | 1.328 | Perf. ‖ 001<br>Dist. ‖ 100,010 | Villiaumite | NaF? | Birefringence very weak |

## B. Isotropic Minerals (Cont.)

II. Isometric (Cont.)

2. Refringence low $>1.52 <1.59$

| COLOR | REFRINGENCE | CLEAVAGE | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|
| Colorless | 1.5247 | | Pollucite | $H_2Cs_4Al_4(SiO_3)_9$ | Crystals cubic |
| | 1.5329 | | Langbeinite | $K_2Mg_2(SO_4)_3$ | Crystals tetrahedral |
| | 1.544 | Perf. ‖ 100 | Halite | $NaCl$ | Rarely violet, yellow, or pink |

3. Refringence moderate $>1.59<1.66$

| | | | | | |
|---|---|---|---|---|---|
| Colorless | 1.6422 | Poor ‖ 111 | Salmiac | $NH_4Cl$ | Found about volcanoes |

4. Refringence high $>1.66<1.75$

| | | | | | |
|---|---|---|---|---|---|
| Yellow | 1.739 | | Helvite | $(Mn,Fe)_2(Mn_2S)Be_3(SiO_4)_3$ | Irregular fracture |
| | ? | Dist. ‖ 100 | Beckelite | $Ca_3(Ce,La,Di)_4Si_3O_{15}$ | Found in pegmatite |
| Colorless to yellow or brown | 1.747 | | **Grossularite** | $Ca_3Al_2(SiO_4)_3$ | Often dodecahedral<br>Sometimes birefringent |
| Colorless to yellow or green | 1.736 | Perf. ‖ 100<br>Poor ‖ 111 | Periclase | $MgO$ | Often cubic |
| Colorless to brown or green | 1.676 | Poor ‖ 100 | Pharmacosiderite | $Fe_4(OH)_3(AsO_4)_3+6H_2O$ | Cubic, tetrahedral<br>Sometimes birefringent |

## B. Isotropic Minerals (Cont.)

II. Isometric (Cont.)

4. Refringence high>1.66<1.75 (Cont.)

| COLOR | REFRINGENCE | CLEAVAGE | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|
| Colorless to yellow, brown, red, blue, green | 1.713-1.725 | Poor ‖ 111 | Spinel | $MgAl_2O_4$ | Often octahedral |
| Green to black | 1.749 | | Hercynite | $FeAl_2O_4$ | Rare |

5. Refringence very high >175

| COLOR | REFRINGENCE | CLEAVAGE | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|
| Colorless | 1.755 | | Arsenolite | $As_2O_3$ | Octahedral, capillary Sometimes birefringent |
| | 2.087 | | Senarmontite | $Sb_2O_3$ | Octahedral. Often distinctly birefringent |
| Colorless to various colors | 2.4195 | Perf. ‖ 111 | Diamond | C | Sometimes weakly birefringent |
| Colorless to yellow | 2.346 | ‖ 110 | Marshite | $Cu_2I_2$ | Tetrahedral |
| | ? | ‖ 110 | Miersite | $Ag_2I_2$ | Cubic |
| Colorless to yellowish brown | 1.747 | | **Grossularite** | $Ca_3Al_2(SiO_4)_3$ | Often dodecahedral. Sometimes weakly birefringent |
| Colorless to gray or violet brown | 2.0611 | | Cerargyrite | AgCl | |
| Colorless to brown, etc. | 2.3692 | Perf. ‖ 110 | **Sphalerite** | ZnS | Rarely weakly birefringent |

## B. Isotropic Minerals. (Cont.)

II. Isometric. (Cont.)

5. Refringence very high >1.75 (Cont.)

| COLOR | REFRINGENCE | CLEAVAGE | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|
| Colorless to pale blue | 2.± | Perf. ‖ 100 | Percylite | $PbCu(OH)_2Cl_2$? | Cubic |
| Yellow | ? | Dist. ‖ 100 | Beckelite | $Ca_3(Ce,La,Di)_4Si_3O_{15}$ | Found in pegmatite |
| Yellow to greenish | 2.2533 | ‖ 110 | Bromyrite | $AgBr$ | |
| Yellow to dark brown | 1.857 | | **Andradite** | $Ca_3Fe_2(SiO_4)_3$ | Often dodecahedral. Sometimes weakly birefringent |
| Brown to yellow | High | | Hatchettolite | Hyd.Ta-niobate of U,Ca, etc. | Octahedral |
| Reddish brown to yellow | High | Indist. ‖ 111 | Pyrochlore | Niobate of Ce,Ca, etc. | Rarely weakly birefringent |
| Orange to red | High | | Pyrrhite | Pyrotantalate of Ca, etc. | Octahedral |
| Red to brown | High | | Koppite | Pyroniobate of Ce,Ca, etc. | Dodecahedral |
| Red to yellowish brown | 1.814 | | **Pyrope** | $Mg_3Al_2(SiO_4)_3$ | Often dodecahedral |
| Brown to reddish | 1.811 | Poor ‖ 110 | **Almandite** | $Fe_3Al_2(SiO_4)_3$ | Often dodecahedral |
| Brown to black | 1.8+ | | Schorlomite | $Ca_3(Fe,Ti)_2(Si,Ti)_3O_{12}$ | Often dodecahedral<br>Rarely weakly birefringent |
| Brown or red to black | 2.0965 | | Chromite | $FeCr_2O_4$ | |

## B. Isotropic Minerals (Cont.)

II. Isometric. (Cont.)

5. Refringence very high>1.75 (Cont.)

| COLOR | REFRINGENCE | CLEAVAGE | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|
| Gray, brown red, greenish | 2.38 | | Perovskite | $CaTiO_3$ | Often distinctly birefringent |
| Green or yellow to brown | 1.765 | Poor ∥ 111 | Gahnite | $ZnAl_2O_4$ | Often octahedral |
| Green | 1.838 | | Uvarovite | $Ca_3Cr_2(SiO_4)_3$ | Often dodecahedral. Sometimes weakly birefringent |
| Pink | 1.799 | | Spessartite | $Mn_3Al_2(SiO_4)_3$ | Often dodecahedral |
| Carmine to crimson | 2.849 | Poor ∣ 100 | Cuprite | $Cu_2O$ | Often octahedral or cubic. Capillary |
| Bright red to opaque | ? | | Tetrahedrite | $Cu_8Sb_2S_7$ | Tetrahedral |

## C. (I). Anisotropic Uniaxial Minerals

I. Refringence very low <1.52

a. Birefringence very weak <0.0035

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Tetr. | Dist. ∥ 001 | Colorless | | 1.494 | 1.491 | 0.003 | Lowéite | $Na_2Mg(SO_4)_2+2\frac{1}{2}H_2O$ | |
| + | Hex. | Perf. ∥ $10\bar{1}0$<br>Poor ∥ 0001 | Colorless | | 1.520 to 1.522 | 1.5174 to 1.520 | 0.0025 to 0.002 | Davyne | Sil. of Al,Na, etc. | |
| + | Ps.Is. Orth.? | Poor ∥ 110 | Colorless | | 1.509 | 1.508 | 0.001 | **Leucite** | $KAlSi_2O_6$ | Often biaxial 2 *V* small |
| ± | Ps.Rh. Tri.? | Dist. ∥ $10\bar{1}1$ | Colorless | | 1.488 | 1.485 | 0.003 | Chabazite | $(Ca,Na_2)Al_2(SiO_3)_4 +6H_2O$ | Often biaxial 2 *V* small |
| ± | Ps.Rh. | Dist. ∥ $10\bar{1}0$ | Colorless | | 1.4646 to 1.4803 | 1.4637 to 1.4785 | 0.0009 to 0.0086 | Gmelinite | $(Na_2,Ca)Al_2(SiO_3)_4 +6H_2O$ | Often biaxial 2 *V* small |
| − | Ps.Is. | | Colorless | | 1.487 | | 0.001 | Analcite | $NaAlSi_2O_6+H_2O$ | Often biaxial 2 *V* small |

b. Birefringence weak >0.0035 <0.0095

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Hex. | | Colorless | | 1.3133 | 1.3090 | 0.0043 | Ice | $H_2O$ | |
| + | Rhom. | Dist. ∥ $10\bar{1}0$ | Colorless | | 1.4993 | 1.4907 | 0.0086 | Aphthitalite | $(K,Na)_2SO_4$ | Sol. in $H_2O$ |
| ± | Ps. Rh. | Dist. ∥ $10\bar{1}0$ | Colorless | | 1.4646 to 1.4803 | 1.4637 to 1.4785 | 0.0009 to 0.0086 | Gmelinite | $(Na_2,Ca)Al_2(SiO_3)_4 +6H_2O$ | Often biaxial 2 *V* small |

## C. (I.) Anisotropic Uniaxial Minerals. (Cont.)

I. Refringence very low $<1.52$ (Cont.)

c. Birefringence moderate $>0.0095$ $<0.0185$

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Tetr. | Perf. ‖ 100<br>Perf. ‖ 110 | Colorless | | 1.3897 | 1.3780 | 0.0117 | Sellaite | $MgF_2$ | |
| + | Hex. | | Colorless | | 1.49 | | 0.010± | Hydronephelite | $HNa_2Al_3(SiO_4)_3+3H_2O$ | |
| — | Hex. | Perf. ‖ 0001 | Colorless | | 1.47 | | 0.014 | Hydrotalcite | $Al(OH)_3 \cdot 3Mg(OH)_2 +3H_2O$ | Fibrous |

d. Birefringence rather strong $>0.0185$ $<0.0275$

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| — | Hex. | Dist. ‖ 0001 | Colorless | | 1.4807 | 1.4614 | 0.0193 | Hanksite | $9Na_2SO_4 \cdot 2Na_2CO_3 \cdot KCl$ | Prisms |

e. Birefringence strong $>0.0275$ $<0.0355$

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| — | Tetr. | | Colorless to yellow | | 1.5393 | 1.5110 | 0.0283 | Mellite | $Al_2C_{12}O_{12}+18H_2O$ | Sometimes biaxial $2E=8° 22'$ |
| — | Hex. | Perf. ‖ $10\bar{1}0$ | Colorless | | 1.5244 | 1.4955 | 0.0289 | Cancrinite | Sil. of Al,Na, etc. | Usually massive |

f. Birefringence strong $>0.0355$ $<0.0445$

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| — | ? | Traces | Colorless | | 1.507 | 1.468 | 0.039 | Thaumasite | $Ca_3CO_3SO_4SiO_3 +15H_2O$ | Massive |

## C. (I). Anisotropic Uniaxial Minerals (Cont.)

1. Refringence very low $<1.52$ (Cont.)

g. Birefringence extreme $>0.0565$.

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| — | Rhom. | Perf. ∥ $10\bar{1}1$ | Colorless | | 1.658 | 1.486 | 0.172 | **Calcite** | $CaCO_3$ | Multiple twinning |
| — | Rhom. | Perf. ∥ $10\bar{1}1$ | Colorless | | 1.682 | 1.503 | 0.179 | **Dolomite** | $(Ca,Mg)CO_3$ | Curved faces |
| — | Rhom. | Perf. ∥ $10\bar{1}1$ | Colorless | | 1.717 | 1.515 | 0.202 | Magnesite | $MgCO_3$ | |
| — | Rhom. | Perf. ∥ $10\bar{1}1$ | Colorless | | 1.587 | 1.336 | 0.251 | Soda Niter | $NaNO_3$ | Sol. in $H_2O$ |

2. Refringence low $>1.52$ $<1.59$

a. Birefringence very weak $<0.0035$

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Hex. | Perf. ∥ $10\bar{1}0$<br>Poor ∥ 0001 | Colorless | | 1.520 to 1.522 | 1.5174 to 1.520 | 0.0025 to 0.002 | Davyne | Sil. of Al, Na, etc. | |
| ± | Tetr. | Perf. ∥ 001<br>Dist. ∥ 110 | Colorless | | 1.5368 | 1.5347 | 0.0021 | Apophyllite | $H_7KCa_4(SiO_3)_8 + 4\frac{1}{2}H_2O$ | Often biaxial |

b. Birefringence weak $>0.0035 < 0.0095$

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Hex. | Perf. ∥ $10\bar{1}0$<br>Poor ∥ 0001 | Colorless | | 1.529 | 1.521 | 0.008 | Microsommite | Sil. of Al, Na, etc | |
| + | Rhom. | | Colorless | | 1.553 | 1.544 | 0.009 | **Quartz** | $SiO_2$ | Rarely biaxial $2E = 12° - 18°$ |
| + | Rhom. | Poor ∥ $10\bar{1}0$, $10\bar{1}1$, $01\bar{1}1$ | Colorless to brown or green | | 1.5547 | 1.5455 | 0.0092 | Coquimbite | $Fe_2(SO_4)_3 + 9H_2O$ | Sol. in $H_2O$ |
| — | Hex. | Poor ∥ $10\bar{1}0$ | Colorless | | 1.5469 | 1.5422 | 0.0047 | **Nephelite** | $K_2Na_6Al_8Si_9O_{34}$ | Alters easily |

## C. (I). Anisotropic Uniaxial Minerals (Cont.)

2. Refringence low >1.52 <1.59 (Cont.)

c. Birefringence moderate >0.0095 <0.0185

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Rhom. | Perf. ‖ 0001 | Colorless | | 1.592 | 1.572 | 0.018 to 0.020 | Alunite | $K_2Al_6S_4O_{22}+6H_2O$ | Elongation—. |
| — | Tetr. | Dist. ‖ 100 | Colorless | | <1.554 | <1.542 | 0.010± | Marialite | $Na_4Al_3Si_9O_{24}Cl$ | Rare |
| — | Tetr. | Dist. ‖ 100 | Colorless | | 1.5545 to 1.562 | 1.5417 to 1.546 | 0.0128 to 0.016 | **Dipyre** | $Me_1Ma_2$ to $Me_1Ma_3$ | Inclusions common |
| — | Tetr. | Perf. ‖ 001 | Colorless to greenish | | 1.592 | 1.582 | 0.010 | Torbernite | $Cu(UO_2)_2(PO_4)_2+8H_2O$ | Rare |

d. Birefringence rather strong >0.0185 <0.0275

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Rhom. | Perf. ‖ 0001 | Colorless | | 1.592 | 1.572 | 0.018 to 0.020 | Alunite | $K_2Al_6S_4O_{22}+6H_2O$ | Elongation—. |
| + | Rhom. | Perf. ‖ 0001 | Colorless to greenish | | 1.581 | 1.560 | 0.021 | Brucite | $Mg(OH)_2$ | Often slightly biaxial |
| + | Rhom. | Perf. ‖ 0001 | Colorless | | ? | ? | Strong | Carphosiderite | $Fe_6S_4O_{21}+10H_2O$ | Related to copiapite |
| — | Tetr. | Dist. ‖ 100<br>Poor ‖ 110 | Colorless | | 1.563 to 1.583 | 1.545 to 1.553 | 0.018 to 0.030 | **Wernerite** | $Me_3Ma_1$ to $Me_1Ma_1$ | Inclusions common |

e. Birefringence strong >0.0275 <0.0355

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Tetr. | Perf. ‖ 110 | Colorless | | 1.5842 | 1.5532 | 0.031 | Narsarsukite | $Na_6FeFTi_2Si_{12}O_{32}$ | Thick sections pleochroic |
| — | Tetr. | Dist. ‖ 100<br>Poor ‖ 110 | Colorless | | 1.563 to 1.583 | 1.545 to 1.553 | 0.018 to 0.030 | **Wernerite** | $Me_3Ma_1$ to $Me_1Ma_1$ | Inclusions common |

## C. (I.) Anisotropic Uniaxial Minerals (Cont.)

2. Refringence low >1.52 <1.59 (Cont.)

e. Birefringence strong >0.0275 <0.0355 (Cont.)

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| — | Tetr. | Dist. ‖ 100<br>Poor ‖ 110 | Colorless |  | 1.583 to 1.597 | 1.552 to 1.560 | 0.031 to 0.037 | Meionite | $Ca_4Al_6Si_6O_{25}$ | Rare |
| — | Tetr. |  | Colorless to yellow |  | 1.5393 | 1.5110 | 0.0283 | Mellite | $Al_2C_{12}O_{12}+18H_2O$ | Sometimes biaxial $2E=8° 22'$ |
| — | Hex. | Perf. ‖ $10\bar{1}0$ | Colorless |  | 1.5244 | 1.4955 | 0.0289 | Cancrinite | Sil. of Al,Na, etc. | Usually massive |
| — | Ps. Hx. Mono. | Perf. ‖ 001 | Z brown or green<br>X yellow | Z>X | 1.574 to 1.638 | 1.541 to 1.586 | 0.033 to 0.060 | **Biotite** | Sil. of Al,Fe,Mg, etc. | Normally biaxial $2V$ small |

f. Birefringence strong >0.0355 <0.0445

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| — | Tetr. | Dist. ‖ 100<br>Poor ‖ 110 | Colorless |  | 1.583 to 1.597 | 1.552 to 1.560 | 0.031 to 0.037 | Meionite | $Ca_4Al_6Si_6O_{25}$ | Rare |
| — | Ps. Hx. Mono. | Perf. ‖ 001 | Z brown or green<br>X yellow | Z>X | 1.574 to 1.638 | 1.541 to 1.586 | 0.033 to 0.060 | **Biotite** | Sil. of Al,Fe,Mg, etc. | Normally biaxial $2V$ small |
| — | Ps. Hx. Mono. | Perf. ‖ 001 | Z yellow<br>X colorless | Z>X | 1.606 | 1.562 | 0.044 | Phlogopite | Sil. of Al,Mg, etc. | Normally biaxial $2V$ small |

g. Birefringence very strong >0.0445 <0.0565

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Hex. | Perf. ‖ $10\bar{1}0$<br>Poor ‖ $11\bar{2}0$ | Colorless |  | 1.613 | 1.558 | 0.055 | Ferrinatrite | $Na_6Fe_2(SO_4)_4+6H_2O$ | Rare |
| — | Ps. Hx. Mono. | Perf. ‖ 001 | Z brown or green<br>X yellow | Z>X | 1.574 to 1.638 | 1.541 to 1.586 | 0.033 to 0.060 | **Biotite** | Sil. of Al,Fe,Mg, etc. | Normally biaxial $2V$ small |

## C. (I.) Anisotropic Uniaxial Minerals (Cont.)

2. Refringence low $>1.52$ $<1.59$ (Cont.)
   h. Birefringence extreme $>0.0565$

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Hex. | Perf. ‖ 0001 | Colorless | | 1.670 | 1.569 | 0.101 | Parisite | $(CeF)_2Ca(CO_3)_3$ | Very rare |
| — | Rhom. | Perf. ‖ 0001 | Colorless to green | | 1.6323 | 1.5745 | 0.0578 | Chalcophyllite | $Cu_7(OH)_8(AsO_4)_2 + 10H_2O$ | Rare |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless | | 1.658 | 1.486 | 0.172 | **Calcite** | $CaCO_3$ | Multiple twinning |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless | | 1.682 | 1.503 | 0.179 | **Dolomite** | $(Ca,Mg)CO_3$ | Curved faces |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless | | 1.717 | 1.515 | 0.202 | Magnesite | $MgCO_3$ | |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless | | 1.587 | 1.336 | 0.251 | Soda Niter | $NaNO_3$ | Sol. in $H_2O$ |

3. Refringence moderate $>1.59$ $<1.66$
   a. Birefringence very weak $<0.0035$

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Hex. | Dist. ‖ 0001<br>Poor $11\bar{2}0$ | Pink | | 1.610 to 1.613 | 1.604 to 1.608 | 0.002 to 0.009 | Eudialyte | Zr sil. of Ca,Na,Fe, etc. | |
| + | Rhom. | None | Yellow in mass | | 1.59 | | Very weak | Chlormanganokalite | $K_4MnCl_6$ | |
| — | Tetr. | Perf. ‖ 001 | Colorless | | 1.6339 | 1.6291 | 0.001 to 0.006 | Melilite | Sil. of Al,Ca | |
| — | Hex. | Dist. ‖ 0001<br>Poor ‖ $11\bar{2}0$ | Pink | | 1.6205 to 1.622 | 1.6178 to 1.618 | 0.0027 to 0.004 | Eucolite | Zr sil. of Ca, Na, Fe, etc. | |
| — | Hex. | | Colorless (or gray, blue or brown) | | 1.6335 to 1.6388 | 1.6316 to 1.6346 | 0.0019 to 0.0042 | **Apatite** | $Ca_4(CaF)(PO_4)_3$ | Rarely biaxial $2E = 10° +$ |

## C. (I.) Anisotropic Uniaxial Minerals (Cont.)

3. Refringence moderate >1.59 <1.66 (Cont.)

b. Birefringence weak >0.0035 <0.0095

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Hex. | Dist. ‖ 0001<br>Poor ‖ $11\bar{2}0$ | Pink | | 1.610 to 1.613 | 1.604 to 1.608 | 0.002 to 0.009 | Eudialyte | Zr sil. of Ca,Na,Fe, etc. | |
| — | Tetr. | Perf. ‖ 001 | Colorless | | 1.6339 | 1.6291 | 0.001 to 0.006 | Melilite | Sil. of Al,Ca | |
| — | Tetr. | Dist. ‖ 001 | Colorless | | 1.663 | 1.658 | 0.005 to 0.006 | Gehlenite | $Ca_3Al_2Si_2O_{10}$ | |
| — | Hex. | Dist. ‖ 0001<br>Poor ‖ $11\bar{2}0$ | Pink | | 1.6205 to 1.622 | 1.6178 to 1.618 | 0.0027 to 0.004 | Eucolite | Zr sil. of Ca,Na,Fe, etc. | |
| — | Hex. | | Colorless (or gray, blue, or brown) | | 1.6391 to 1.648 | 1.6341 to 1.643 | 0.0034 to 0.005 | **Apatite** | $Ca_4(CaCl)(PO_4)_3$ | Rarely biaxial $2E=10°+$ |
| — | Hex. | Poor ‖ 0001 | Colorless | | 1.5785 to 1.5825 | 1.5735 to 1.5761 | 0.005 to 0.0064 | Beryl | $Be_3Al_2(SiO_3)_6$ | Thick sections pleochroic |

c. Birefringence moderate >0.0095 <0.0185

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Rhom. | Traces | Colorless | | 1.6697 | 1.6540 | 0.0157 | Phenacite | $Be_2SiO_4$ | Thick sections pleochroic |
| — | Tetr. | Perf. ‖ 001<br>Dist. ‖ 100 | Colorless to green | | 1.64 | | ? | Zeunerite | $Cu(UO_2)_2(AsO_4)_2 + 8H_2O$ | Rare |
| — | Tetr. | Dist. ‖ 001<br>Poor ‖ 100 | Colorless | | 1.6691 | 1.6568 | 0.0123 | Hardystonite | $Ca_2ZnSi_2O_7$ | Granular |
| — | Rhom. | | Z colorless to pink<br>X colorless | Z>X | 1.6377 to 1.6507 | 1.6199 to 1.6257 | 0.0146 to 0.0211 | Li Tourmaline | Sil. of B,Al,Li, etc. | |

## C. (I.) Anisotropic Uniaxial Minerals (Cont.)

3. Refringence moderate >1.59 <1.66 (Cont.)

d. Birefringence rather strong >0.0185 <0.0275

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| — | Tetr. | Dist. ‖ 001 | Colorless | | 1.6126 | 1.5934 | 0.0192 | Meliphanite | $NaCa_2Be_2FSi_3O_{10}$ | |
| — | Rhom. | | Z yellow, brown, green, blue, X colorless, yellow, brown, gray | Z>X | 1.631 to 1.685 | 1.612 to 1.651 | 0.019 to 0.034 | Mg **Tourmaline** and Fe **Tourmaline** | Sil. of B,Al,Mg,Fe, etc. | |

e. Birefringence strong >0.0275 <0.0355

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| — | Rhom. | | Z brown green, blue X yellow, brown, gray | Z>X | 1.6424 to 1.6854 | 1.6222 to 1.6515 | 0.0202 to 0.0339 | Fe **Tourmaline** | Sil. of B,Al,Fe, etc. | |
| — | Rhom. | Perf. ‖ 0001 | Colorless to pink | Z>X | ? | ? | Strong | Friedelite | $H_7(MnCl)Mn(SiO_4)_4$ | Thick plates pleochroic |
| — | Rhom. | Perf. ‖ 0001<br>Poor ‖ 10$\bar{1}$0 | Colorless to yellow, gr'n | ? | 1.66 | | Strong | Pyrosmalite | Fe Friedelite | |

f. Birefringence strong >0.0355 <0.0445

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Tetr. | ? | Rose red in mass | ? | 1.64 | | Strong | Sarcolite | $(Ca,Na_2)_3Al_2(SiO_4)_3$ | Like scapolite |
| — | Ps. Hx. Mono. | Perf. ‖ 001 | Z brown or green X yellow | Z>X | 1.574 to 1.638 | 1.541 to 1 586 | 0.033 to 0.060 | **Biotite** | Sil. of Al,Fe,Mg, etc. | Normally biaxial $2V$ small |
| — | Ps. Hx. Mono. | Perf. ‖ 001 | Z yellow X colorless | Z>X | 1.606 | 1.562 | 0.044 | Phlogopite | Sil. of Al,Mg, etc. | Normally biaxial $2V$ small |

## C. (I.) Anisotropic Uniaxial Minerals (Cont.)

3. Refringence moderate $>1.59$ $<1.66$ (Cont.)

g. Birefringence very strong $>0.0445$ $<0.0565$

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Hex. | Perf. ‖ $10\bar{1}0$<br>Poor ‖ $11\bar{2}0$ | Colorless | | 1.613 | 1.558 | 0.055 | Ferrinatrite | $Na_6Fe_2(SO_4)_4+6H_2O$ | |
| — | Rhom. | Perf. 0001 | Z green, X blue green | ? | 1.694 | 1.641 | 0.053 | Spangolite | Sul. of Al,Cu etc. | |
| — | Ps. Hx.<br>Mono. | Perf. ‖ 001 | Z brown or green<br>X yellow | Z>X | 1.574 to 1.638 | 1.541 to 1.586 | 0.033 to 0.060 | **Biotite** | Sil. of Al,Fe,Mg, etc. | Normally biaxial $2V$ small |
| | h. Birefringence extreme $>0.0565$ | | | | | | | | | |
| + | Hex. | Perf. ‖ 0001 | Colorless | | 1.670 | 1.569 | 0.101 | Parisite | $(CeF)_2Ca(CO_3)_3$ | |
| — | Rhom. | Perf. ‖ 0001 | Colorless to green | | 1.6323 | 1.5745 | 0.0578 | Chalcophyllite | $Cu_7(OH)_8(AsO_4)_2 + 10H_2O$ | |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless | | 1.658 | 1.486 | 0.172 | **Calcite** | $CaCO_3$ | Multiple twinning |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless | | 1.682 | 1.503 | 0.179 | **Dolomite** | $(Ca,Mg)CO_3$ | Curved faces |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless | | 1.717 | 1.515 | 0.202 | Magnesite | $MgCO_3$ | |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless to gray | | 1.873 | 1.633 | 0.240 | **Siderite** | $FeCO_3$ | Absorption weak |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Pink in mass | | 1.82± | 1.597 | 0.222 | Rhodochrosite | $MnCO_3$ | |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless | | 1.818± | 1.618 | 0.200 | Smithsonite | $ZnCO_3$ | |

## C. (I.) Anisotropic Uniaxial Minerals (Cont.)

4. Refringence high $>1.66 < 1.75$

a. Birefringence very weak $>.00035$

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| ∓ | Tetr. | Poor ∥ 110 | Colorless or brownish, greenish | | 1.705 to 1.732 | 1.701 to 1.726 | 0.001 to 0.006 | Vesuvianite | Sil. of Al,Ca, etc. | Sometimes biaxial $2E=30°\text{-}60°$ |

b. Birefringence weak $>0.0035 < 0.0095$

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ∓ | Tetr. | Poor ∥ 110 | Colorless or brownish, greenish | | 1.705 to 1.732 | 1.701 to 1.726 | 0.001 to 0.006 | Vesuvianite | Sil. of Al,Ca. etc. | Sometimes biaxial $2E=30°\text{-}60°$ |

c. Birefringence moderate $>0.0095 < 0.0185$

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Rhom. | Traces | Colorless | | 1.6697 | 1.6540 | 1.0157 | Phenacite | $Be_2SiO_4$ | Thick sections pleochroic |
| — | Tetr. | Dist. ∥ 001<br>Poor ∥ 100 | Colorless | | 1.6691 | 1.6568 | 0.0123 | Hardystonite | $Ca_2ZnSi_2O_7$ | Granular |

d. Birefringence rather strong $>0.0185 < 0.0275$

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Rhom. | Dist. ∥ $11\bar{2}0$ or 0001 | Colorless | | 1.7118 | 1.6931 | 0.0187 | Willemite | $Zn_2SiO_4$ | |

e. Birefringence strong $>0.0275 < 0.0355$

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| — | Rhom. | | Z brown, green, blue, X yellow, brown, grey | Z>X | 1.642 to 1.685 | 1.622 to 1.652 | 0.020 to 0.034 | Fe **Tourmaline** | Sil. of B,Al,Fe, etc. | |
| — | Rhom.? | Perf. ∥ 0001 | Yellow to brown | ? | 1.73 | | Strong | Hematolite | Arsen. of Al,Mn, etc. | Often biaxial $2E$ small |

## C. (I). Anisotropic Uniaxial Minerals (Cont.)

4. Refringence high >1.66 <1.75 (Cont.)

f. Birefringence strong >0.0355 <0.0445

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| — | Rhom. | Perf. ‖ 0001 | Colorless to brown | Z>X | 1.723 | 1.681 | 0.042 | Pyrochroite | $Mn(OH)_2$ | Like brucite |
| — | Rhom. | Perf. ‖ 0001 | Colorless to pink | Z>X | ? | ? | Strong | Friedelite | $H_7(MnCl)Mn(SiO_4)_4$ | Thick plates pleochroic |
| — | Rhom. | Perf. ‖ 0001<br>Poor ‖ $10\bar{1}0$ | Colorless to yellow, green | ? | 1.66 |  | Strong | Pyrosmalite | Fe Friedelite |  |
| g. Birefringence very strong >0.0445 <0.0565 |  |  |  |  |  |  |  |  |  |  |
| + | Rhom. | Perf. ‖ $10\bar{1}1$ | Green | ? | 1.723 | 1.667 | 0.056 | Dioptase | $H_2CuSiO_4$ |  |
| — | Rhom. | Perf. ‖ 0001 | Z green<br>X blue green | ? | 1.694 | 1.641 | 0.053 | Spangolite | Sul. of Al,Cu, etc. |  |
| h. Birefringence extreme >0.0565 |  |  |  |  |  |  |  |  |  |  |
| + | Tetr. | Perf. ‖ 110 | Colorless or yellow | ? | 1.81 | 1.72 | 0.090 | Xenotime | $YPO_4$ |  |
| + | Hex. |  | Yellow or gray |  | 1.7701 | 1.6742 | 0.0959 | Synchysite | $(CeF)Ca(CO_3)_2$ | Brown pigment |
| + | Hex. | Perf. ‖ 0001 | Colorless |  | 1.670 | 1.569 | 0.101 | Parisite | $(CeF)_2Ca(CO_3)_3$ |  |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless |  | 1.682 | 1.503 | 0.179 | **Dolomite** | $(Ca,Mg)CO_3$ | Curved faces |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless |  | 1.717 | 1.515 | 0.202 | Magnesite | $MgCO_3$ |  |

## C. (I.) Anisotropic Uniaxial Minerals. (Cont.)

4. Refringence high >1.66 <1.75 (Cont.)

h. Birefringence extreme >0.0565 (Cont.)

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless to gray | ? | 1.873 | 1.633 | 0.240 | **Siderite** | $FeCO_3$ | Absorption weak |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Pink in mass | | 1.82± | 1.597 | 0.222 | Rhodochrosite | $MnCO_3$ | |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless | | 1.818± | 1.618 | 0.200 | Smithsonite | $ZnCO_3$ | |

5. Refringence very high >1.75

a. Birefringence very weak <0.0035

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Tetr. | Dist. ‖ 110 | Colorless to brown, gray | | 1.826 | | very weak | Zircon (altered) | $ZrSiO_4(+H_2O)$ | |
| + | Tetr. | Dist. ‖ 110 | Colorless to brown | | ? | ? | weak | Thorite (altered) | $ThSiO_4(+H_2O)$ | |

b. Birefringence weak >0.0035 <0.0095

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Hex. | Dist. ‖ $11\bar{2}0$ | Yellow in mass | | ? | 2.688 | weak | Greenockite | CdS | |
| — | Hex. | Traces | Variable | | 2.050 | 2.042 | 0.008 | Pyromorphite | $Pb_4(PbCl)(PO_4)_3$ | Sometimes biaxial |
| — | Rhom. | | Colorless to blue, green, red | Z>X | 1.767 | 1.759 | 0.008 | **Corundum** | $Al_2O_3$ | Sometimes biaxial |

## C. (I). Anisotropic Uniaxial Minerals (Cont.)

5. Refringence very high >1.75 (Cont.)

c. Birefringence moderate >0.0095 <0.0185

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Tetr. | Dist. \|\| 111 | Colorless or yellow, green | | 1.935 | 1.919 | 0.016 | Scheelite | $CaWO_4$ | |
| + | Tetr. | Dist. \|\| 110 | Colorless to brown, gray | | 1.84± | | ? | Zircon (altered) | $ZrSiO_4(+H_2O)$ | |
| + | Tetr. | Dist. \|\| 110 | Colorless to brown | | ? | ? | ? | Thorite (altered) | $ThSiO_4(+H_2O)$ | |
| — | Hex. | | Colorless to brown in mass | | 2.135 | 2.118 | 0.017 | Mimetite | $Pb_4(PbCl)(AsO_4)_3$ | Usually biaxial $2E=64°$— |

d. Birefringence rather strong >0.0185 <0.0275

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Tetr. | Dist. \|\| 110 and 100 | Colorless | | 2.140 | 2.114 | 0.026 | Phosgenite | $(PbCl)_2CO_3$ | |
| + | Hex. | Perf. \|\| 0001 | Red in mass | | 2.± | | 0.021± | Zincite | $ZnO$ | |
| + | Hex. | Dist. \|\| $11\bar{2}0$ | Yellow | X>Z | ? | ? | 0.020 | Wurtzite | $ZnS$ | |
| — | Tetr. | Perf. \|\| 100 | Blue? | | 2.± | | 0.020 | Boléite | $PbCu(OH)_2Cl_2$? | |

e. Birefringence strong >0.0275 <0.0355

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Tetr. | Dist. \|\| 110 | Colorless to brown, gray | | 1.882 | | 0.034 | Zircon (altered) | $ZrSiO_4(+H_2O)$ | |
| + | Tetr. | Dist. \|\| 110 | Colorless to brown | | ? | ? | ? | Thorite (altered) | $ThSiO_4(+H_2O)$ | |

## C. (I). Anisotropic Uniaxial Minerals (Cont.)

5. Refringence very high >1.75 (Cont.)

e. Birefringence strong >0.0275 <0.0355 (Cont.)

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Hex. | Poor ‖ $10\bar{1}1$ | Z blue to colorless<br>X colorless | Z>X | 1.80 | 1.77 | 0.03 | Benitoite | $BaTiSi_3O_9$ | Color quite variable |
| — | Tetr. | Perf. ‖ 100 | Blue? |  | 2.± |  | 0.032 | Pseudoboléite | $PbCu(OH)_2Cl_2$? |  |

f. Birefringence strong >0.0355 <0.0445

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Tetr. | Dist. ‖ 110 | Colorless to brown, gray |  | 1.968 | 1.924 | 0.044 | Zircon (altered) | $ZrSiO_4(+H_2O)$ |  |
| — | Tetr. | Dist. ‖ 001<br>Dist. ‖ 111 | Blue or yellow |  | 2.534 to 2.562 | 2.496 to 2.489 | 0.038 to 0.073 | Octahedrite | $TiO_2$ | Thick sections pleochroic with X>Z |

g. Birefringence very strong >0.0445 <0.0565

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Tetr. | Dist. ‖ 110 | Colorless to brown |  | ? | ? | ? | Thorite | $ThSiO_4$ |  |
| + | Tetr. | Dist. ‖ 110 | Colorless to brown, gray |  | 1.9832 | 1.9302 | 0.053 | Zircon | $ZrSiO_4$ | Large crystals biaxial $2V=10°$ |
| — | Tetr. |  | Colorless to yellow |  | 2.354 | 2.299 | 0.055 | Vanadinite | $Pb_4(PbCl)(VO_4)_3$ |  |
| — | Hex. | Perf. ‖ 0001 | Colorless |  | 1.8148 | 1.7611 | 0.0537 | Molybdophyllite | $(Pb,Mg)_2SiO_4+H_2O$ | Micaceous |

## C. (I.) Anisotropic Uniaxial Minerals (Cont.)

5. Refringence very high >1.75 (Cont.)

h. Birefringence extreme >0.0565

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| + | Tetr. | Dist. ‖ 100 and ‖ 110 | Z brown, green, X yellow, brown | Z>X | 2.9029 | 2.6158 | 0.2871 | **Rutile** | $TiO_2$ | Acicular. Geniculated twinning |
| + | Tetr. | Dist. ‖ 100 | Colorless to brown | ? | 2.093 | 1.997 | 0.097 | Cassiterite | $SnO_2$ | Sometimes biaxial 2*V* small |
| + | Tetr. | Dist. ‖ 100 | Colorless to brown | ? | ? | ? | ? | Thorite | $ThSiO_4$ | |
| + | Tetr. | | Brown | ? | ? | ? | ? | Plattnerite | $PbO_2$ | |
| + | Tetr. | Perf. ‖ 110 | Colorless or yellow | ? | 1.81 | 1.72 | 0.090 | Xenotime | $YPO_4$ | |
| + | Tetr. | Dist. ‖ 100 | Colorless | | 2.656 | 1.973 | 0.683 | Calomel | $H_3Cl$ | |
| + | Hex. | Perf. ‖ $10\bar{1}0$ | Red in mass | ? | 3.201 | 2.854 | 0.347 | **Cinnabar** | $HgS$ | |
| + | Hex. | | Yellow or gray | | 1.7701 | 1.6742 | 0.0959 | Synchysite | $(CeF) Ca(CO_3)_2$ | Brown pigment |
| + | Hex. | Perf. ‖ 0001 | Yellow in mass | ? | 2.1816 | | ? | Iodyrite | $AgI$ | Isometric at 140°C. |
| — | Tetr. | Dist. ‖ 001<br>Dist. ‖ 111 | Blue or yellow | | 2.554 to 2.562 | 2.493 to 2.489 | 0.061 to 0.073 | Octahedrite | $TiO_2$ | Thick sections pheochroic with Z>X |
| — | Tetr. | Dist. ‖ 111 | Colorless | | 2.402 | 2.304 | 0.098 | Wulfenite | $PbMoO_4$ | |

## C. (I.) Anisotropic Uniaxial Minerals (Cont.)

5. Refringence very strong $>1.75$ (Cont.)

h. Birefringence extreme $>0.0565$ (Cont.)

| SIGN | SYST. | CLEAVAGE | COLOR | ABSP. | $n_g$ | $n_p$ | $n_g - n_p$ | NAME | COMPOSITION | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| — | Tetr. | Poor ‖ 001 | Colorless | | 2.268 | 2.182 | 0.086 | Stolzite | $PbWO_4$ | |
| — | Tetr. | Perf. ‖ 100 | Blue ? | | 2± | | 0.100 | Cumengéite | $PbCu(OH)_2Cl_2$? | |
| — | Rhom. | | Z brown, red, X yellow, red | Z>X weak | 3.042 | 2.797 | 0.245 | **Hematite** | $Fe_2O_3$ | Often opaque |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless to gray | ? | 1.873 | 1.633 | 0.240 | **Siderite** | $FeCO_3$ | Absorption weak |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Pink in mass | | 1.82± | 1.597 | 0.222 | Rhodochrosite | $MnCO_3$ | |
| — | Rhom. | Perf. ‖ $10\bar{1}1$ | Colorless | | 1.818± | 1.618 | 0.200 | Smithsonite | $ZnCO_3$ | |
| — | Rhom. | Dist. ‖ $10\bar{1}1$ | Red | ? | 3.084 | 2.881 | 0.203 | **Pyrargyrite** | $Ag_3SbS_3$ | |
| — | Rhom. | Dist. ‖ $10\bar{1}1$ | Bright red | ? | 3.088 | 2.792 | 0.295 | Proustite | $Ag_3AsS_3$ | |
| — | Rhom. | Perf. ‖ $02\bar{2}1$ | Yellow red | | 2.481 | 2.210 | 0.271 | Pyrophanite | $MnTiO_3$ | Scaly |
| — | Rhom. | Perf. ‖ $02\bar{2}1$? | Purple | | Very high | | Very strong | Geikielite | $MgTiO_3$ | |
| — | Orth. | Perf. ‖ 010<br>Dist. ‖ 110 | Colorless | | 2.34 | | ? | Valentinite | $Sb_2O_3$ | Biaxial, but $2V=0°$ nearly |

## O. Indices unknown

| SIGN | SYST. | ELONGATION Sign | ELONGATION Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE |
|---|---|---|---|---|---|---|---|---|
| ? | Mono. | Pyram. | | $? \wedge c = 5\frac{1}{2}°$ | | Colorless | | Dist. $\parallel$ 100 |
| ? | Mono. | ? | $\parallel c$ | Opt. Pl. $\parallel$ elong.<br>$\perp$ cleav. ± | | Colorless | | $\parallel$ elong. |
| ? | ? | ? | ? | $? \wedge c = -69\frac{1}{2}°$ | | Colorless | | $\parallel$ 010 |
| + | Orth. | + | $\parallel c$ ? | $Z \parallel c$ | $X \parallel b$ | Colorless | | Dist. $\parallel$ 001 |
| + | Orth. | + | $\parallel$ 010 | $X \parallel b$ | $Z \parallel a$ | Yellow in mass | ? | Perf. $\parallel$ 010 |
| + | Orth. | + | $\parallel c$ | $Z \parallel c$ | $X \parallel b$ | Red in mass | ? | Dist. $\parallel$ 010 |
| + | Orth. | ± | $\parallel$ 001 | $Y \parallel c$ | $Z \parallel b$ | Z orange brown<br>Y yellow green<br>X brown green | ? | ? |
| + | Mono. | ? | ? | $Z \wedge a = 42°$ | $Y \parallel b$ | Yellow to brown | Pleoch. | Perf. $\parallel$ 100<br>Poor $\parallel$ 010 |
| + | Mono. | | | 7° to 15° | $X \parallel b$ | Colorless | | Perf. $\parallel$ 100<br>Perf. $\parallel$ 001 |
| + | Mono. | + | $\parallel$ 001 | $Z \wedge c = -67°$ | $Y \parallel b$ | Green in mass | ? | Perf. $\parallel$ 001 |
| + | Mono. | + | $\parallel c$ | +17° | $X \parallel b$ | Z green<br>Y yellow, brown | ? | Perf. $\parallel$ 010 |
| + | Mono. | — | $\parallel c$ | $X \wedge c = 45°$ | $Z \parallel b$ | Brown | Weak | None? |
| — | Orth. | + | $\parallel$ 001 | $X \parallel c$ | $Z \parallel b$ | Colorless? | | Perf. $\parallel$ 001 |
| — | Orth. | + | $\parallel c$ | $Z \parallel c$ | $X \parallel b$ | Z pink to colorless<br>Y deep pink<br>X yellowish | ? | Dist. $\parallel$ 100 |
| — | Orth. | + | $\parallel$ 010 | $X \parallel b$ | $Z \parallel c$ | Z brown-yellow<br>Y orange- "<br>X pale yellow | $Z > Y > X$ | Perf. $\parallel$ 010<br>Poor $\parallel$ 001,100 |
| — | Orth. | + | $\parallel c$ | $Z \parallel c$ | $X \parallel b$ | Greenish | ? | Perf. $\parallel$ 010 |
| — | Orth. | + | $\parallel$ 001 | $X \parallel c$ | $Z \parallel b$ | Blue green | ? | ? |
| — | Orth. | + | $\parallel$ 001 | $X \parallel c$ | $Z \parallel a$ | Z blue<br>Y=X green | ? | Perf. $\parallel$ 001<br>Poor $\parallel$ 100 |
| — | Orth. | + | $\parallel c$ | 0° | $Z \parallel c$ ? | Blue | Strong | ? |
| — | Orth. | ± | $\parallel c$ | $Y \parallel c$ | $X \parallel b$ | Brown (pleoch.) | $Y > X > Z$? | Perf. $\parallel$ 010<br>Perf. $\parallel$ 110 |
| — | Orth. | — | $\parallel$ 001 | $Z \parallel c$ | $X \parallel b$ | Colorless | | Poor $\parallel$ 100 |
| — | Orth. | — | $\parallel c$? | $X \parallel c$ | $Y \parallel b$ | Blue to green pleochroic | ? | $\parallel$ 001<br>$\parallel$ 010 |
| — | Mono. | | Pyr. | $X \wedge c = -25°$ | $Z \parallel b$ | Colorless to yellow | ? | Dist. $\parallel$ 110 |
| — | Mono. | ? | ? | $Z \wedge c = +75°$ | $X \parallel b$ | Red to gray in mass | ? | Dist. $\parallel$ 100 |

## Biaxial Minerals.

| $n_m$ | $n_p$ | $n_g - n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|
| ? | ? | ? | $2E=110°$ | Incl. marked | Cuspidine | $Ca_3SiO_4$ with $CaF_2$? |
| ? | ? | Strong | Large | ? | Dawsonite | $NaAl(OH)_2CO_3$ |
| ? | ? | ? | $2E=55°$ | $\rho<v$ cross. | Wapplerite | $HCaAsO_4+3\frac{1}{2}H_2O$ |
| ? | ? | ? | $2H_o=119°$ | $\rho>v$ | Molybdite | $MoO_3$ |
| ? | ? | ? | $2E=70°$ | $\rho>v$ very strong | Orpiment | $As_2S_3$ |
| ? | ? | ? | $2E=70° \pm$ | $\rho>v$ | Hemafibrite | $Mn_3(OH)_3AsO_4+H_2O$ |
| ? | ? | ? | Large | $\rho<v$ | Flinkite | $MnAsO_4 \cdot 2Mn(OH)_2$ |
| ? | ? | ? | $2H=95°$ | $\rho>v$ Incl. dist. | Triplite | $(Fe,MnF)(Fe,Mn)PO_4$ |
| ? | ? | ? | $2H=104°$ | ? | Heintzite | $KMg_2B_9O_{16}+8H_2O$ |
| ? | ? | ? | $2V=82°$ | $\rho>v$ | Ludlamite | Phos. of Fe,H |
| ? | ? | ? | $2V=75°$ | ? | Hübnerite | $MnWO_4$ |
| ? | ? | ? | Small | ? | Synadelphite | Ars. of Mn,Al,H |
| ? | ? | ? | $2E=108°$ | $\rho<v$ weak | Lanthanite | $La_2(CO_3)_3+9H_2O$ |
| ? | ? | ? | $2H=54°$ | $\rho<v$ | Eosphorite | Phos. of Al,Mn,H |
| ? | ? | ? | Very large | Moderate | Lepidocrocite | $FeO(OH)$? |
| ? | ? | ? | $2H=96° \pm$ | ? | Brochantite | $Cu_4(OH)_6SO_4$ |
| ? | ? | ? | $2E=67°$ | $\rho>v$ strong | Serpierite | Sul. of Zn,Cu,H |
| ? | ? | ? | $2H=76°$ | $\rho<v$ | Gerhardtite | $Cu(NO_3)_2 \cdot 3Cu(OH)_2$ |
| ? | ? | ? | ? | $\rho<v$ strong | Cyanotrichite | Sul. of Al,Cu,H |
| ? | ? | Strong | Small | $\rho>v$ very strong | Manganite | $MnO(OH)$ |
| ? | ? | ? | $2E=74° \pm$ | $\rho>v$ marked | Childrenite | Phos. of Al,Fe,H |
| ? | ? | ? | ? | ? | Langite | $Cu_4(OH)_6SO_4+H_2O$ |
| ? | ? | ? | $2H=81°$ | $\rho>v$ weak horiz. | Durangite | $Na(AlF)AsO_4$ |
| ? | ? | ? | $2E=174°$ | $\rho>v$ strong crossed | Hureaulite | $H_2Mn_5PO_4+4H_2O$ |

O. **Indices unknown (Cont.)**

| SIGN | SYST. | ELONGATION |  |  | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE |
|---|---|---|---|---|---|---|---|---|
|  |  | Sign | Direc. | Ext. Ang. |  |  |  |  |
| — | Mono. |  |  | $Z \wedge c = -25^\circ$ | $X \parallel b$ | Blue to green in mass | ? | Poor $\parallel$ 110 |
| — | Mono. | + | $\parallel$ 001 | $X \wedge c = 1^\circ \pm$ | $Z \parallel b$ | Z yellow green<br>Y blue green | ? | Perf. $\parallel$ 001<br>Dist. $\parallel$ 110 |
| — | Mono. | ± | $\parallel b$ | 0° | $Y \parallel b$ | Colorless |  | Perf. $\parallel$ 001 |
| — | Mono. | ± | $\parallel c$ | $Y \wedge c = -28^\circ$ | $Z \parallel b$ | ? | ? | Perf. $\parallel$ 010 |
| — | Mono. | ± | $\parallel b$ | $Y \parallel b$ | $X \wedge c = -54^\circ$ | Red in mass | ? | Prism? |
| — | Mono. | — | $\parallel$ 010 | $X \wedge c = +62^\circ \pm$ | $Z \parallel b$ | Colorless |  | $\parallel$ 010 |
| — | Mono. | — | $\parallel c$ | $Z \wedge c = +10^\circ$. | $Y \parallel b$ | Blue, green? | ? | Perf. $\parallel$ 001 |
| — | Tri. | + | $\parallel c$ | Ext. on 010 $= -16^\circ$ | $X \perp 100 \pm$ | Orange | ? | Perf. $\parallel$ 100<br>Perf. $\parallel$ 010 |
| — | Tri. | + | $\parallel$ 001 | $X \wedge c = 30^\circ$ | Ext. on 001 $= 30^\circ \pm$ | Brown to yellow in mass | ? | Perf. $\parallel$ 010 |
| — | Tri. | — | $\parallel c$ | $X \wedge c = +23^\circ$ | $Z \wedge b = 5^\circ$ | Z blue green<br>Y yellow green<br>X blue green | $Z > X > Y$ | Poor $\parallel$ 010 |

Refringence very low $<1.52$

*a.* Birefringence unknown.

|  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
| ? | Orth. |  |  | $Bx \parallel c$ | Opt. Pl. $\parallel$ 100 | Colorless |  | Poor $\parallel$ 111 |
| ? | Mono. | ? | $\parallel c$ | $Bx \parallel a \pm$ | $Y \parallel b$ | Colorless |  | ? |
| + | Orth. | + | $\parallel c$ | $Z \parallel c$ | $X \parallel a$ | Colorless |  | Perf. $\parallel$ 010 |
| + | Orth. | ± | varies | $X \parallel c$ | $Z \parallel b$ | Colorless |  | Perf. $\parallel$ 001<br>Dist. $\parallel$ 010 |
| + | Mono. |  |  | $X \wedge c = +4^\circ$ | $Y \parallel b$ | Blue in mass | ? | ? |
| + | Mono. |  |  | $X \wedge c = -1^\circ$ | $Y \parallel b$ | Colorless |  | ? |
| + | Mono. |  | Pyr. | $Z \wedge c = 76^\circ$ | $Y \parallel b$ | Colorless |  | Perf. $\parallel$ 111 |
| + | Mono. | ± | $\parallel c$ | $Z \wedge c = +68^\circ$ | $X \parallel b$ | Colorless |  | Poor $\parallel$ 001 |
| — | Mono. |  |  | $X \wedge c = -52^\circ$ | $Z \parallel b$ | Colorless |  | Perf. $\parallel$ 001 |
| — | Mono. | + | $\parallel c$ | $Z \wedge c = +30^\circ$ | $X \parallel b$ | Colorless |  | Perf. $\parallel$ 100 |
| — | Mono. | — | $\parallel c$ | $X \wedge c = -44^\circ$ | $Y \parallel b$ | Colorless |  | None? |
| — | Mono. | — | $\parallel b$ | $Z \wedge c = 83^\circ$ | $X \parallel b$ | Colorless |  | Perf. $\parallel$ 100 |

| $n_m$ | $n_p$ | $n_g-n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|
| ? | ? | ? | $2E=133^\circ$ | $\rho<v$ | Liroconite | Ars. of Al,Cu,H |
| ? | ? | ? | $2E=66^\circ$ | $\rho<v$ strong | Herrengrundite | $(Cu,Ca)_5(OH)_6(SO_4)_2+3H_2O$ |
| ? | ? | Strong | $2H=65^\circ$ | ? | Lanarkite | $Pb_2SO_5$ |
| ? | ? | Not strong | ? | ? | Clinohedrite | $ZnCa(OH)_2SiO_3$ |
| ? | ? | ? | $2V=83^\circ$ | ? | Sarkinite | $Mn_3(AsO_4)_2\cdot Mn(OH)_2$ |
| ? | ? | ? | $2H=112^\circ$ | ? | Copiapite | $Fe_4S_5O_{21}+18H_2O$ |
| ? | ? | ? | $2E=137^\circ\pm$ | $\rho<v$ strong.Incl. | Clinoclasite | $Cu_3(OH)_3AsO_4$ |
| ? | ? | ? | $2E=63^\circ$ | $\rho<v$ strong | Amarantite | $Fe_2S_2O_9+7H_2O$ |
| ? | ? | ? | $2H=58^\circ$ | ? | Römerite | $FeFe_2(SO_4)_4+12H_2O$ |
| ? | ? | ? | ? | ? | Pseudomalachite | $Cu_3P_2O_8\cdot 2Cu(OH)_2$ |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1.47 | ? | ? | $2E=100^\circ\pm$ | ? | Fluellite | $AlF_3+H_2O$ |
| 1.474 | ? | ? | $2E=77^\circ$ | $\rho>v$ | Boussingaultite | $(NH_4)_2Mg(SO_4)_2+6H_2O$ |
| 1.5196 | ? | ? | $2V=45^\circ$ | $\rho<v$ | Newberyite | $HMgPO_4+3H_2O$ |
| 1.502 | ? | ? | $2E=60^\circ\pm$ | $\rho<v$ strong | Struvite | $NH_4MgPO_4+6H_2O$ |
| 1.491 | ? | ? | $2V=49^\circ$ | $\rho>v$ | Cyanochroite | $K_2Cu(SO_4)_2+6H_2O$ |
| 1.47 | ? | ? | $2V=48^\circ$ | $\rho>v$ | Picromerite | $K_2Mg(SO_4)_2+6H_2O$ |
| 1.46 | ? | ? | $2E=90^\circ$ | $\rho<v$ Incl. dist. | Kieserite | $MgSO_4+H_2O$ |
| ? | ? | ? | $2E=120^\circ\pm$ | $\rho<v$ weak horiz. | Pachnolite | $NaCaAlF_6+H_2O$ |
| ? | ? | ? | $2E=70^\circ$ | $\rho<v$ weak | Thomsenolite | $NaCaAlF_6+H_2O$ |
| ? | ? | ? | $2E=123^\circ$ | crossed strong | Mirabilite | $Na_2SO_4+10H_2O$ |
| 1.500 | ? | ? | $2V=70^\circ$ | Incl. dist. | Blödite | $MgNa_2(SO_4)_2+4H_2O$ |
| 1.50 | ? | ? | $2E=137^\circ$ | $\rho<v$ | Trona | $HNa_3(CO_3)_2+2H_2O$ |

## 1. Refringence very low < 1.52

### a. Birefringence very weak < 0.0035

| SIGN | SYST. | ELONGATION | | | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE |
|---|---|---|---|---|---|---|---|---|
| | | Sign | Direc. | Ext. Ang. | | | | |
| + | Orth.?<br>Ps. Is. | | | | $Z \parallel a$ | Colorless | | |
| + | Orth.<br>Ps. Hx. | — | ∥ 001 | $Z \parallel c$ | $X \parallel b$ | Colorless | | |
| + | Mono. | + | $\parallel a$ | $Z \wedge a = -20°$ | $X \parallel b$ | Colorless | | Dist. ∥ 001<br>Dist. ∥ 010 |
| + | Tri. | + | $\parallel c$ | $Z \wedge c = 20°$ | ? | Colorless | | Dist. ∥ $1\bar{1}0$<br>Dist. ∥ $1\bar{1}0$ |
| ± | Tri.<br>Ps. Hx. | | | Bx. ⊥ 0001± | | Colorless | | Dist. ∥ $10\bar{1}1$ |
| — | Ps. Is. | | | | | Colorless | | |

### b. Birefringence weak > 0.0035 < 0.0095

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ? | Mono. | ± | $\parallel c$ | $Y \wedge c = +17°$ | $X \parallel b$ | Colorless | | Perf. ∥ 010 |
| + | Orth. | varies | | $Z \parallel a$ | $X \parallel b$ | Colorless | | Dist. ∥ 001 |
| + | Mono. | | | $Z \wedge c = -44°$ | $X \parallel b$ | Colorless | | Perf. ∥ 001<br>Dist. ∥ 110 |
| + | Mono. | ± | $\parallel a$ | $X \wedge a = +62° \pm$ | $Z \parallel b$ | Colorless | | Dist. ∥ 010 |
| + | Mono. | — | ∥ 010 | varies | $Z \parallel b$ | Colorless | | Perf. ∥ 010 |
| + | Tri. | ± | $\parallel c$ | $Y \wedge c = 5° \pm$ | $Z \parallel a \pm$ | Colorless | | Perf. ∥ $1\bar{1}0$<br>Perf. ∥ $1\bar{1}0$ |
| ± | Ps. Hx. | | | | | Colorless | | Dist. ∥ $10\bar{1}0$ |
| — | Mono. | —<br>or ± | $\parallel a$<br>or $\parallel c$ | $X \wedge a = +5°$ | $Z \parallel b$ | Colorless | | Perf. ∥ 001<br>Dist. ∥ 010 |
| — | Mono. | — | $\parallel a$ | $X \wedge a = +5°$ | $Y \parallel b$ | Colorless | | Perf. ∥ 010 |
| — | Mono. | — | $\parallel c$ | $X \wedge c = +15°$ | $Z \parallel b$ | Colorless | | Perf. ∥ 110 |
| — | Tri. | — | ∥ 010 | Ext. on 010 = +5° | Ext. on 001 = +15° | Colorless | | Perf. ∥ 001<br>Dist. ∥ 010 |

### c. Birefringence moderate > 0.0095 < 0.0185

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| + | Orth. | + | $\parallel c$ | $Z \parallel c$ | $X \parallel a$ | Colorless | | Perf. ∥ 110 |
| + | Orth. | — | $\parallel c$ | $X \parallel c$ | ? | Colorless | | ? |
| + | Mono. | — | $\parallel c$ | $X \wedge c = +22°$ | $Z \parallel b$ | Colorless | | Perf. ∥ 010 |
| + | Mono. | — | $\parallel a$ | $X \wedge a = -8°$ | $Z \parallel b$ | Colorless | | Perf. ∥ 001 |

|  | $n_m$ | $n_p$ | $n_g - n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|---|
| 9 |  | 1.508 | 0.001 | Very small | ? | **Leucite** | $KAlSi_2O_6$ |
|  | 1.478 | ? | 0.002 | $2E=66°$ | ? | Tridymite | $SiO_2$ |
|  | 1.48 to 1.51 | ? | 0.003 | $2V=70°$ | $\rho<v$ weak | Phillipsite | $(K_2,Ca)Al_2(SiO_3)_4+4H_2O$ |
|  | Very low | ? | 0.002± | Very small | ? | Pseudomesolite | Sil. of Al,Ca,Na,H |
| 3 | ? | 1.485 | 0.003 | Small | ? | Chabazite | $(Ca,Na_2)Al_2(SiO_3)_4+6H_2O$ |
|  | 1.487 | ? | 0.001 | Very small | ? | Analcite | $NaAl(SiO_3)_2+H_2O$ |

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
|  | Very low | ? | Weak | $2V$ large | ? | Mordenite | Sil. of Al,Ca,Na,K,H |
|  | 1.470 | ? | ? | $2E=153°$ | $\rho>v$ weak | Thenardite | $Na_2SO_4$ |
|  | 1.364 | ? | Weak | $2E=59°$ | $\rho<v$ Horiz. | Cryolite | $Na_3AlF_6$ |
| 8 | ? | 1.503 | 0.005 | $2H=87°$ | Crossed weak | Harmotome | Sil. of Al,K,Ba,H |
| 5 | 1.499 | 1.498 | 0.007 | $2E=52°\pm$ | Crossed strong | Heulandite | $H_4CaAl_2(SiO_3)_6+3H_2O$ |
|  | Very low | ? | 0.005± | $2V$ large | $\rho>v$ dist. | Mesolite | Sil. of Al,Ca,Na,H |
| 46<br>03 | ? | 1.4637<br>-1.4785 | 0.0009<br>-0.0086 | $2V$ small | ? | Gmelinite | Sil. of Al,Ca,Na,H |
| 60 | 1.5237 | 1.5190 | 0.007 | $2V=69°\pm$ | $\rho>v$ Horiz. | **Orthoclase** | $KAlSi_3O_8$ |
| 0 | 1.498 | 1.494 | 0.006 | $2E=52°\pm$ | ? | **Stilbite** | Sil. of Al,Ca,Na,H |
| 94 | 1.5187 | 1.5122 | 0.007 | $2E=55°\pm$ | $\rho<v$ | Scolecite | $CaAl_2Si_3O_{10}+3H_2O$ |
| 63 | 1.5236 | 1.5194 | 0.007 | $2V=83°\pm$ | $\rho>v$ Horiz. | **Microcline** | $KAlSi_3O_8$ |

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| 5<br>3 | 1.476<br>-1.482 | 1.473<br>-1.480 | 0.012<br>-0.013 | $2E=94°\pm$ | $\rho<v$ weak | **Natrolite** | $Na_2Al_2Si_3O_{10}+2H_2O$ |
|  | Very low | ? | 0.017 | $2V$ small | ? | Lintonite | Sil. of Al,Ca,Na,H |
|  | 1.45 | ? | 0.012 | $2E=98°\pm$ | $\rho>v$ weak | Brewsterite | Sil. of Al,Sr,Ba,Ca,H |
| 5 | 1.510 | 1.504 | 0.012 | $2V=83°$ | $\rho<v$ weak | Petalite | $LiAl(Si_2O_5)_2$ |

1. **Refringence very low <1.52 (Cont.)**

**c. Birefringence moderate >0.0095 <0.0185. (Cont.)**

| SIGN | SYST. | ELONGATION |  |  | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Sign | Direc. | Ext. Ang. |  |  |  |  |  |
| — | Mono. | + | ∥ *c* | $Z \wedge c = +9^\circ$ | Y ∥ *b* | Colorless |  | Perf. ∥ 010 | 1. |
| — | Mono. | + | ∥ *c* | $Z \wedge c = -27^\circ$ | Y ∥ *b* | Colorless |  | Perf. ∥ 010<br>Perf. ∥ 110 | 1.5 |
| — | Mono. | ± | ∥ *c* | $Y \wedge c = -3^\circ$ | Z ∥ *b* | Colorless |  | Perf. ∥ 110<br>Perf. ∥ 100 | 1.5 |

**d. Birefringence rather strong >0.0185 <0.0275**

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE |  |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth. |  |  | Z ∥ *a* | X ∥ *c* | Colorless |  | None | 1.4 |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *b* | Colorless |  | Dist. ∥ 110<br>Dist. ∥ 010 |  |
| + | Orth. | ± | ∥ *c* | X ∥ *a* | Z ∥ *b* | Colorless |  | Perf. ∥ 010 | 1.5 |
| — | Orth. | ± | ∥ *c* | Z ∥ *a* | X ∥ *b* | Colorless |  | Perf. ∥ 010 | 1.4 |
| — | Orth. | ± | ∥ *c* | Z ∥ *a* | X ∥ *b* | Colorless |  | Perf. ∥ 010 | 1.4 |
| — | Mono. | + | ∥ 001 | $X \wedge c = -9^\circ$ | Y ∥ *b* | Colorless |  | Perf. ∥ 100<br>Dist. ∥ 110 | 1. |
| — | Mono. | ± | ∥ *c* | $X \wedge c = -56^\circ$ | X ∥ *b* | Colorless |  | Perf. ∥ 100<br>Dist. ∥ 110 | 1. |
| — | Tri. | + | ∥ 001 | X⊥ 001± | Opt. Pl. ∥ *b*± | Colorless |  | Perf. ∥ 001 |  |

**e. Birefringence strong >0.0275 <0.0355**

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE |  |
|---|---|---|---|---|---|---|---|---|---|
| + | Mono.? | ± | ∥ 010 | $Z \wedge c = -50^\circ \pm$ | Y ∥ *b* | Colorless |  | Dist. ∥ 211 |  |
| + | Mono. | — | ∥ *c* | $Z \wedge c = -61^\circ$ | Y ∥ *b* | Colorless |  | Perf. ∥ 001 |  |
| + | Mono. | — | ∥ *c*? | Z ∥ *a*± | Y ∥ *b* | Blue in mass | ? | Perf. ∥ 001 |  |
| + | Mono. | — | ∥ *c*? | Z ∥ *a*± | Y ∥ *b* | Blue in mass | ? | Perf. ∥ 001 |  |
| — | Orth. | ± | ∥ *c* | Z ∥ *a* | X ∥ *b* | Colorless |  | Perf. ∥ 010 | 1. |
| — | Orth. | ± | ∥ *c* | X ∥ *a* | Z ∥ *b* | Colorless |  | Perf. ∥ 110 | 1. |

**g. Birefringence extreme >0.0565**

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE |  |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth. | ± | ∥ *c* | X ∥ *a* | Z ∥ *b* | Colorless |  | None | 1. |
| + | Mono. |  |  | $Z \wedge c = -11^\circ$ | X ∥ *b* | Colorless |  | ∥ 001, 010, 110 | 1. |
| — | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *b* | Colorless |  | Perf. ∥ 011<br>Poor ∥ 010 | 1. |
| — | Mono. | ± | ∥ *a* | $Z \wedge c = -14^\circ$ | X ∥ *b* | Colorless |  | Perf. ∥ 110 | 1. |

## xial Minerals (Cont.)

| $n_m$ | $n_p$ | $n_g-n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|
| 1.510 | 1.502 | 0.010 | $2E=72°\pm$ | $\rho<v$ dist. | Epistilbite | $H_4CaAl_2(SiO_3)_6+3H_2O$ |
| 1.524 | 1.513 | 0.012 | $2E=54°$ | $\rho<v$ strong | Laumontite | $H_4CaAl_2Si_4O_{14}+2H_2O$ |
| 1.517 | 1.5000 | 0.0183 | $2E=44°$ | $\rho<v$ dist. | Syngenite | $K_2Ca(SO_4)_2+H_2O$ |
| 1.4753 | 1.4665 | 0.0272 | $2E=115°$ | $\rho<v$ | Carnallite | $KMgCl_3+6H_2O$ |
| 1.526 | ? | 0.025 | $2V=70°\pm$ | ? | Wavellite | $(AlOH)_3(PO_4)_2 \cdot 5H_2O$ |
| 1.503 | 1.498 | 0.027 | $2E=87°$ | $\rho>v$ dist. | **Thomsonite** | Sil. of Al,Ca,Na,H |
| 1.4801 | 1.4568 | 0.027 | $2E=70°$ | $\rho<v$ weak | Goslarite | $ZnSO_4+7H_2O$ |
| 1.4888 | 1.4669 | 0.025 | $2E=64°$ | $\rho>v$ dist. | Morenosite | $NiSO_4+7H_2O$ |
| 1.5061 | 1.4947 | 0.0256 | $2V=84°$ | Incl. dist. | Kainite | $MgSO_4 \cdot KCl+3H_2O$ |
| 1.4686 | 1.4468 | 0.0247 | $2E=59°$ | $\rho>v$ cross'd dist. | **Borax** | $Na_2B_4O_7+10H_2O$ |
| 1.46 | ? | Rather strong | $2E=11°$ | None | Sassolite | $H_3BO_3$ |
| 1.502 | ? | Strong | $2E=103°$ | $\rho>v$ strong | Prosopite | $CaAl_2(F,OH)_8$ |
| 1.47 | ? | ? | $2V=86°$ | $\rho>v$ | Melanterite | $FeSO_4+7H_2O$ |
| ? | ? | ? | $2H=86°$ | ? | Pisanite | $(Fe,Cu)SO_4+7H_2O$ |
| ? | ? | ? | ? | ? | Boothite | $CuSO_4+7H_2O$ |
| 1.4554 | 1.4325 | 0.028 | $2E=78°$ | $\rho>v$ weak | Epsomite | $MgSO_4+7H_2O$ |
| 1.501 | 1.495 | 0.031 | $2E=84°$ | $\rho<v$ weak | Nesquehonite | $MgCO_3+3H_2O$ |
| 1.5095 | 1.5043 | 0.071 | $2E=48°$ | ? | Pirssonite | $CaNa_2(CO_3)_2+2H_2O$ |
| 1.5552 | 1.4900 | 0.1597 | $2V=84°$ | $\rho<v$ weak | Whewellite | $CaC_2O_4+H_2O$ |
| 1.505 | 1.334 | 0.172 | $2E=9°$ | ? | Niter | $KNO_3$ |
| 1.5156 | 1.4435 | 0.080 | $2E=52°$ | $\rho<v$ cros'd strong | Gaylussite | $CaNa_2(CO_3)_2+5H_2O$ |

2. Refringence low > 1.52 < 1.59

a. Birefringence unknown

| SIGN | SYST. | ELONGATION | | | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
| | | Sign | Direc. | Ext. Ang. | | | | | |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *b* | Green in mass | ? | ? | ? |
| — | Mono. | + | ∥ 001 | X ⊥ 001± | Y ∥ *b* | Colorless | | Perf. ∥ 001 | ? |

a. Birefringence very weak <0.0035

| SIGN | SYST. | ELONGATION | | | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
| | | Sign | Direc. | Ext. Ang. | | | | | |
| + | Orth.? | + | ∥ *c* | Z ∥ *c* | ? | Green | ? | ? | ? |
| ± | Mono. | ± | ∥ 001 | 0°± | Y ∥ *b* | Z=Y green<br>X colorless ± | Z=Y>X | Perf. ∥ 001 | 1.57 |
| — | Mono.? | + | ∥ 001 | 0°± | ? | Z=Y blue<br>X colorless ± | Z=Y>X | Perf. ∥ 001 | ? |

b. Birefringence weak >0.0035 <0.0095

| SIGN | SYST. | ELONGATION | | | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
| | | Sign | Direc. | Ext. Ang. | | | | | |
| + | Rhom. | | | 0° | Z ∥ *c* | Colorless | | None | 1.55 |
| + | Mono. | ± | ∥ 010 | Z∧*c*= +52° | Y ∥ *b* | Colorless | | Perf. ∥ 010 | 1.52 |
| + | Mono. | ± | ∥ 001 | Z∧*c*= —58° | Y ∥ *b* | Colorless | | Perf. ∥ 001 | 1.5 |
| + | Mono. | — | ∥ 001 | 0°± | Y ∥ *b* | Z pale green, yellow or brown<br>Y=X green | Z<Y=X | Perf. ∥ 001 | ? |
| + | Tri. | — or ± | ∥ *a* or ∥ *c* | Ext. on 010= +20° | Ext. on 001= +4° | Colorless | | Perf. ∥ 001<br>Dist. ∥ 010 | 1.5 |
| + | Tri. | — or ± | ∥ *a* or ∥ *c* | Ext. on 010=—4° to —10° | Ext. on 001= 0° to —2° | Colorless | | Perf. ∥ 001<br>Dist. ∥ 010 | 1.5 |
| + | Tri. | — or ± | ∥ *a* or ∥ *c* | Ext. on 010 =—20° to —25° | Ext. on 001=—5° to —11° | Colorless | | Perf. ∥ 001<br>Dist. ∥ 010 | 1.5<br>-1.5 |
| ± | Tri. | — or ± | ∥ *a* or ∥ *c* | Ext. on 010=0° to +15° | Ext. on 001= 0° to +2° | Colorless | | Perf. ∥ 001<br>Dist. ∥ 010 | 1.5<br>-1.5 |
| ± | Tri. | — or ± | ∥ *a* or ∥ *c* | Ext. on 010= — 33° | Ext. on 001= —18° | Colorless | | Perf. ∥ 001<br>Dist. ∥ 010 | 1.5<br>-1.5 |
| — | Orth. | + | ∥ 001 | X ∥ *c* | Z ∥ *b* | Colorless | | Perf. ∥ 001<br>Poor ∥ 100 | 1.5 |
| — | Orth. | + | ∥ *c* | Z ∥ *c* | ? | Colorless | | Poor ∥ *c* | ? |
| — | Orth. | + | ∥ 100 | X ∥ *a* | Z ∥ *c* | Z greenish<br>Y=X colorless | weak Z>Y=X | Perf. ∥ 100 | ? |
| — | Orth. | ± | ∥ 001 | X ∥ *b* | Y ∥ *c* | Colorless | | Perf. ∥ 100<br>Perf. ∥ 010 | 1.5 |
| — | Orth. | ± | ∥ *c* | Y ∥ *c* | X ∥ *b* | Colorless | | Perf. ∥ 100<br>Dist. ∥ 010 | |
| — | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *b* | Usually colorless. Z bluish<br>Y blue or brown<br>X yellow or colorless | rare Y>Z>X | Dist. ∥ 010 | 1.5<br>-1.5 |

## ial Minerals (Cont.)

| $n_m$ | $n_p$ | $n_g-n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|
| 1.555 | ? | ? | $2E=106°$ | ? | Fischerite | $AlPO_4 \cdot Al(OH)_3$ |
| 1.54± | ? | ? | $2E=112°±$ | ? | Sepiolite | $H_8Mg_2(SiO_4)_3$ |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1.59 | ? | Weak | $2V$ small | ? | Garnierite | Sil. of Mg,Ni,H |
| ? | 1.576 | 0.003 | $2E$ small | strong | **Penninite** | Sil. of Al,Mg,Fe,H |
| ? | ? | ? | $2V$ small | strong | Ærinite | ? |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 1.5442 | 0.0091 | Uniax'l. Rarely $2E=45°±$ | ? | **Quartz**<br>See quartzine, etc. | $SiO_2$ |
| 1.5227 | 1.5204 | 0.0092 | $2E=95°$ | $\rho>v$<br>Incl. strong | **Gypsum** | $CaSO_4+2H_2O$ |
| 1.5457 | 1.5453 | 0.0055 | $2V=29°$ | $\rho>v$<br>dist. | Eudidymite | $HNaBeSi_3O_8$ |
| 1.58 | ? | ? | Varies<br>$2V=20°±$ | $\rho<v$ | Chlorite (Prochlorite) | Sil. of Al,Fe,Mg,H |
| 1.5331 | 1.529 | 0.010 | $2V=77°±$ | $\rho<v$<br>Incl. | **Albite** | $NaAlSi_3O_8$ |
| 1.553 | 1.549 | 0.007 | $2V=87°$ to 90° | $\rho<v$<br>horiz. | **Andesine** | $Ab_2An_1$ to $Ab_4An_3$ |
| 1.5578<br>-1.5639 | 1.5548<br>-1.5611 | 0.0075<br>-0.008 | $2V=77°$ to 80° | $\rho>v$<br>crossed | **Labradorite** | $Ab_1An_1$ to $Ab_1An_2$ |
| 1.5415<br>-1.5458 | 1.5373<br>-1.5417 | 0.0084<br>-0.0073 | $2V=80°$ to 90° | $\rho<v$<br>$\rho>v$<br>crossed | **Oligoclase** | $Ab_{12}An_1$ to $Ab_3An_1$ |
| 1.573<br>-1.579 | 1.569<br>-1.574 | 0.009 | $2V=80°$ to 90° | $\rho>v$<br>$\rho<v$ | **Bytownite**<br>(*cf.* **Anorthite**) | $Ab_1An_3$ to $Ab_1An_8$ |
| 1.5579 | 1.5520 | 0.0088 | $2E=121°$ | $\rho<v$<br>weak | Beryllonite | $NaBePO_4$ |
| 1.556 | ? | 0.009 | $2V$ large | ? | Okenite | $H_2CaSi_2O_6+H_2O$ |
| 1.570 | ? | 0.007± | $2E=110°±$ | $\rho>v$<br>weak | **Antigorite** | $H_4Mg_3Si_2O_9$ |
| 1.5685 | 1.5645 | 0.0043 | $2V=31°$ | ? | Epididymite | $HNaBeSi_3O_8$ |
| 1.59± | ? | weak | $2E=20°$ to 32° | $\rho<v$<br>weak | β-Hopeite | $Zn_3P_2O_8+4H_2O$ |
| 1.532<br>-1.562 | 1.534<br>-1.552 | 0.006<br>-0.011 | $2V=39°$ to 84° | $\rho<v$<br>weak | **Cordierite** | Sil. of Al,Mg,Fe,H |

2. **Refringence low >1.52 <1.59 (Cont.)**

**b. Birefringence weak >0.0035 <0.0095 (Cont.)**

| SIGN | SYST. | ELONGATION | | | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
| | | Sign | Direc. | Ext. Ang. | | | | | |
| — | Mono.<br>Ps. Tet. | | | Z ∥ *a* ± | X ∥ *b* | Colorless | | None | ? |
| — | Mono. | + | ∥ 001 | Z∧*c*=<br>—13° | Z ∥ *b* | Colorless | | Perf. ∥ 001 | ? |
| — | Mono.? | + | ∥ 001 | 0° ± | ? | Z, Y blue<br>X colorless | Z=Y>X | Perf. ∥ 001 | ? |
| — | Mono. | —<br>or ± | ∥ *a*<br>or ∥ *c* | X∧*a*=<br>—5°<br>to —20° | Z ∥ *b* | Colorless | | Perf. ∥ 001<br>Dist. ∥ 010 | 1.54 |
| — | Mono. | —<br>or ± | ∥ *a*<br>or ∥ *c* | X∧*a*=<br>+5° | Z ∥ *b* | Colorless | | Perf. ∥ 001<br>Dist. ∥ 010 | 1.52 |
| — | Tri. | —<br>or ± | ∥ *a*<br>or ∥ *c* | Ext. on<br>010=+5° | Ext. on<br>001=<br>+15° | Colorless | | Perf. ∥ 001<br>Dist. ∥ 010 | 1.52 |
| — | Tri. | —<br>or ± | ∥ *a*<br>or ∥ *c* | Ext. on<br>010=+9° ± | Ext. on<br>001=+2° | Colorless | | Perf. ∥ 001<br>Dist. ∥ 010 | 1.53 |

**c. Birefringence moderate >0.0095 <0.0185**

| SIGN | SYST. | ELONGATION | | | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
| | | Sign | Direc. | Ext. Ang. | | | | | |
| ? | Orth. | ± | ∥ *c* | ? | Y ∥ *c* | Colorless | | | 1.53 |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *a* | Z pale green or yellowish<br>Y=X colorless | Z>Y=X | ∥ *c* | ? |
| + | Orth. | + | ∥ *c* | Z ∥ *c* ? | ? | Green? | ? | ? | ? |
| + | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *a* | Colorless to red in mass | ? | ? | 1.57 |
| + | Mono. | | | Z ∥ *c* ± | Y ∥ *b* | Colorless | | None | 1.58 |
| + | Mono. | +<br>or — | ∥ *a*<br>or ∥ *c* | Z∧*a*=<br>+28° | Y ∥ *b* | Colorless | | Perf. ∥ 001<br>Dist. ∥ 010 | 1.59 |
| + | Mono. | ± | ∥ 001 | Z∧*c*=<br>—34° | Y ∥ *b* | Colorless | | Perf. ∥ 110 | 1.58 |
| + | Mono. | — | ∥ *c* | X∧*c*=<br>10° | Z ∥ *b* | Colorless | | Perf. ∥ 010 | 1.55 |
| + | Mono. | — | ∥ 001 | Z ⊥ 001 ± | Y ∥ *b* | Z colorless<br>Y=X green | Z<Y=X | Perf. ∥ 001 | 1.59 |
| + | Mono. | — | ∥ 001 | Z∧*c* =8° | Y ∥ *b* | Green in mass | ? | Perf. ∥ 001 | ? |
| — | Orth. | | | X ∥ *c* | Z ∥ *a* | Colorless | | Perf. ∥ 110 | 1.55 |
| — | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *a* | Colorless<br>Rarely<br>Z blue or yellow<br>Y blue or brown<br>X colorless | Rare<br>Y>Z>X | Dist. ∥ 010 | 1.54<br>to<br>1.56 |
| — | Mono. | + | ∥ *c* | Z∧*c*=<br>27° ± | Y ∥ *b* | Colorless | | Perf. ∥ 010 | 1.52 |
| — | Mono. | + | ∥ 001 | X ⊥ 001 ± | ? | Z=Y green<br>X colorless<br>rarely Z—Y pink | Z=Y>X | Perf. ∥ 001 | ? |
| — | Mono. | + | ∥ 001 | X ⊥ 001 ± | ? | Z=Y pale green<br>X colorless | Z=Y>X | Perf. ∥ 001 | ? |

| $n_m$ | $n_p$ | $n_g - n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|
| 1.5385 | ? | ? | 2*V*=82° | ? | Gismondite | $CaAl_2Si_4O_{12}+4H_2O$ |
| 1.55 | ? | 0.007 | 2*V*=90°± | ? | **Kaolinite** | $H_4Al_2Si_2O_9$ |
| ? | ? | ? | 2*V* small | Strong | Ærinite | ? |
| 1.5451 | 1.5419 | 0.005 | 2*V*=79°± | $\rho>v$<br>Horiz. | Hyalophane | $(K_2,Ba)Al_2Si_4O_{12}$ |
| 1.5237 | 1.5190 | 0.007 | 2*V*=69°± | $\rho>v$<br>Horiz. | **Orthoclase** | $KAlSi_3O_8$ |
| 1.5236 | 1.5194 | 0.007 | 2*V*=83°± | $\rho>v$<br>Horiz. | **Microcline** | $KAlSi_3O_8$ |
| 1.5294 | 1.5234 | 0.007 | 2*V*=45°± | $\rho>v$<br>Horiz. | Anorthoclase | $(K,Na)AlSi_3O_8$ |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1.530+ | 1.523? | 0.015± | 2*V* large | ? | Hydromagnesite | $3MgCO_3{\cdot}Mg(OH)_2+3H_2O$ |
| 1.54± | ? | 0.013 | 2*E*=32°± | ? | **Chrysotile** | $H_4Mg_3Si_2O_9$ |
| 1.55 | ? | ? | 2*E* small | ? | Deweylite | $H_{12}Mg_4Si_3O_{16}$ |
| 1.5650 | 1.5600 | 0.0139 | 2*V*=75° | $\rho<v$<br>dist. | Elpidite | $Na_2Zr(Si_2O_5)_3$ |
| 1.570 | 1.569 | 0.013 | 2*V*=26°± | $\rho>v$<br>dist. | Wagnerite | $(MgF)MgPO_4$ |
| 1.5886 | 1.5835 | 0.0106 | 2*V*=87°± | ? | Celsian | $BaAl_2Si_2O_8$ |
| 1.5759 | 1.5736 | 0.0141 | 2*E*=85° | ? | Augelite | $Al(OH)_3AlPO_4$ |
| 1.5455 | 1.5392 | 0.0117 | 2*V*=86° | ? | Brushite | $HCaPO_4+2H_2O$ |
| 1.588 | 1.585 | 0.011 | 2*E*=40°±<br>varies | $\rho<v$ | **Clinochlore** | Sil. of Al,Mg,Fe,H |
| 1.583 | ? | ? | 2*E*=65°±<br>varies | $\rho<v$ | Corundophilite | Sil. of Al,Fe,Mg,H |
| 1.5492 | 1.5382 | 0.0158 | 2*E*=87° | $\rho<v$ | Edingtonite | $BaAl_2Si_3O_{10}+3H_2O$ |
| 1.538<br>to<br>1.562 | 1.534<br>to<br>1.552 | 0.006<br>to<br>0.011 | 2*V*=39°<br>to<br>84° | $\rho<v$<br>weak | **Cordierite** | Sil. of Al,Fe,Mg,H |
| 1.524 | 1.513 | 0.012 | 2*E*=52° | $\rho<v$<br>strong | Laumontite | $H_4CaAl_2Si_4O_{14}+2H_2O$ |
| ? | ? | 0.014 | 2*V* small | ? | **Delessite** | Sil. of Al,Fe,Mg,H |
| ? | ? | 0.010<br>-0.012 | 2*V* small | ? | Chamosite | Sil. of Al,Mg,Fe,H |

2. Refringence low >1.52 <1.59 (Cont.)

c. Birefringence moderate >0.0095 <0.0185 (Cont.)

| SIGN | SYST. | ELONGATION | | | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | *n* |
|---|---|---|---|---|---|---|---|---|---|
| | | Sign | Direc. | Ext. Ang. | | | | | |
| — | Mono. | — | ∥ *a* | X∧*a*= +27° | Z ∥ *b* | Colorless | | Perf. ∥ 010 | 1. |
| — | Tri. | —<br>or ± | ∥ *a*<br>or ∥ *c* | Ext. on 010= —42° | Ext. on 001= —37° | Colorless | | Perf. ∥ 001<br>Dist. ∥ 010 | 1. |

d. Birefringence rather strong >0.0185 <0.0275

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | *n* |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *a* | Colorless | | Dist. ∥ 110<br>Dist. ∥ 010 | |
| + | Orth.? | + | ∥ *c* ? | ? | Z ∥ *c*? | Z gold yellow<br>Y, X yellowish | Z>Y=X | ? | |
| + | Mono. | — | ∥ 001 | Z∧*c*= 21° to 44° | X ∥ *b* | Colorless | | Perf. ∥ 001 | 1.5 |
| — | Orth. | + | ∥ 001 | X ∥ *c* | Z ∥ *b* | Colorless | | Perf. ∥ 001<br>Dist. ∥ 100<br>Dist. ∥ 010 | 1.5 |
| — | Orth.? | + | ∥ 001? | 0° | X ∥ *c*? | Yellow to colorless | ? | Dist. ∥ 001? | |
| — | Orth. | + | ∥ 001 | X ∥ *c* | Z ∥ *a* | Golden yellow | None | Perf. ∥ 001 | 1.5 |
| — | Orth.? | + | ∥ 100 | X ∥ *a* | Z ∥ *c* | Z green or dark red yellow<br>Y, X green or yellow | Z>Y>X | Perf. ∥ 100 | |
| — | Orth. | ± | ∥ *c* | Y ∥ *c* | X ∥ *b* | Colorless | | Perf. ∥ 100<br>Dist. ∥ 010 | |
| — | Orth. | — | ∥ 001 | X ∥ *a* | Z ∥ *c* | Colorless | | 001, 110, 010, 100 | 1. |
| — | Mono.? | + | ∥ 001 | X ∥ *c*± | ? | Z, Y yellow<br>X colorless | Z=Y>X | Perf. ∥ 001 | |
| — | Tri. | | | X ∥ 001 and 1$\bar{1}$0 | | Colorless | | Perf. ∥ 001<br>Dist. ∥ 1$\bar{1}$0 | 1. |

e. Birefringence strong >0.0275 <0.0355

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | *n* |
|---|---|---|---|---|---|---|---|---|---|
| + | Mono. | | | Z∧*c*= —12° | X ∥ *b* | Z orange, Y pink to colorless. X pale yellow to colorless | Z>Y>X | Dist. ∥ 110 | 1. |
| — | Orth. | + | ∥ 001? | X ∥ *c*± | ? | Colorless | | Perf. ∥ 001? | |
| — | Orth.? | + | ∥ 001? | X ∥ *c*± | ? | Colorless | | Perf. ∥ 001? | |
| — | Mono. | + | ∥ 001 | X ∥ *c*± | Z ∥ *b* | Colorless | | Perf. ∥ 001 | 1.<br>-1. |
| — | Mono. | + | ∥ 001 | X ∥ *c*± | Y ∥ *b* | Z, Y brown or green<br>X yellow | Z>Y>X | Perf. ∥ 001 | 1.<br>-1. |
| — | Mono. | + | ∥ 001 | X ∥ *c*± | Y ∥ *b* | Z, Y brown<br>X colorless | Y>Z>X | Perf. ∥ 001 | 1.5 |
| — | Tri. | | | X between —*a*,+*b*,+*c* | | Colorless | | Perf. ∥ 1$\bar{1}$0<br>110, 111 | 1. |

## axial Minerals (Cont.)

| | $n_m$ | $n_p$ | $n_g-n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|---|
| 37 | 1.5891 | 1.5825 | 0.0112 | $2H=112°$ | $\rho>v$ | Pharmacolite | $HCaAsO_4+2H_2O$? |
| 34 | 1.5837 | 1.5757 | 0.0127 | $2V=75°$ to 78° | $\rho<v$ | **Anorthite** | $CaAl_2Si_2O_8$ |

| | $n_m$ | $n_p$ | $n_g-n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|---|
| | 1.526 | ? | 0.025 | $2V=70°\pm$ | ? | Wavellite | $(AlOH)_3P_2O_8 \cdot 5H_2O$ |
| | ? | ? | 0.026 | $2E=20°\pm$ | ? | Xylotile | Sil. of Fe,Mg,H |
| 77 | 1.5347 | 1.5347 | 0.023<br>-0.019 | $2V=0°$ to 40° | $\rho>v$<br>dist. | Hydrargillite | $Al(OH)_3$ |
| 79 | 1.5948 | 1.5709 | 0.027 | $2E=74°$ | $\rho>v$<br>weak | Leucophane | $Na(BeF)Ca(SiO_3)_2$ |
| | >1.54 | ? | 0.021 | $2E=48°\pm$ | $\rho>v$ | Astrolite | Sil. of Al,Fe,Na,K,H |
| 7 | 1.575 | 1.553 | 0.024 | $2E=60°$ | $\rho>v$ | Autunite | $Ca(UO_2)_2P_2O_8+8H_2O$ |
| | 1.57± | ? | 0.025± | $2E=0°$ to 40° | ? | **Bowlingite** | Sil. of Fe,Mg,Al,H |
| | 1.59± | ? | strong | $2E=58°\pm$ | $\rho<v$<br>weak | α-Hopeite | $Zn_3P_2O_8+4H_2O$ |
| 1 | 1.593 | 1.588 | 0.023 | $2V=75°\pm$ | $\rho>v$ | Bertrandite | $H_2Be_4Si_2O_9$ |
| | ? | ? | 0.020+ | $2E=55°\pm$ | ? | Chloropal | $H_6Fe_2(SiO_4)_3+2H_2O$ |
| 7 | 1.593 | 1.578 | 0.019 | $2V=52°\pm$ | $\rho>v$<br>Incl. cross'd | Amblygonite | $Li\left\{Al(F,OH)\right\}PO_4$ |

| | $n_m$ | $n_p$ | $n_g-n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|---|
| 2 | 1.548 | 1.544 | 0.028 | $2V=41°$ | $\rho>v$ | Botryogen | $Mg(FeOH)(SO_4)_2+7H_2O$ |
| | ? | ? | strong | $2E=40°\pm$ | ? | Bravaisite | Sil. of Fe,Mg,K,Ca,H |
| | ? | ? | 0.03± | $2E=20°\pm$ | ? | Thermophyllite | Sil. of Al,Mg,Na,H |
| | 1.587<br>-1.593 | 1.557<br>-1.560 | 0.033<br>-0.049 | $2E=70°\pm$ | $\rho>v$<br>weak | **Muscovite** | $H_2(K,Na)Al_3(SiO_4)_3$ |
| | 1.574<br>-1.638 | 1.541<br>-1.586 | 0.033<br>-0.060 | $2E=0°$ to 15° | $\rho<v$ | **Biotite** | Sil. of Al,Fe,Mg,H |
| ± | 1.582 | 1.554 | 0.028 | $2E$ small | ? | Levérrierite | Hyd. alum. sil. |
| 64 | 1.5394 | 1.5156 | 0.0308 | $2E=93°$ | $\rho<v$ | Chalcanthite | $CuSO_4+5H_2O$ |

### 2. Refringence low $>1.52$ $<1.59$ (Cont.)

#### f. Birefringence strong $>0.0355$ $<0.0445$

| SIGN | SYST. | ELONGATION |  |  | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n$ |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Sign | Direc. | Ext. Ang. |  |  |  |  |  |
| + | Orth. |  |  | $X \parallel c$ | $Z \parallel a$ | Colorless |  | Perf. ∥ 001<br>Perf. ∥ 010<br>Dist. ∥ 100 | 1.6 |
| — | Orth.? | + | ∥ 001 | $X \parallel c\pm$ | $Z \parallel b$ | Colorless |  | Perf. ∥ 001 | 1.5 |
| — | Mono.? | + | ∥ 001 | $X \parallel c\pm$ | ? | Colorless |  | Perf. ∥ 001 | ? |
| — | Mono. | + | ∥ 001 | $X \parallel c\pm$ | $Z \parallel b$ | Colorless |  | Perf. ∥ 001 | 1.5<br>-1.6 |
| — | Mono. | + | ∥ 001 | $X \parallel c\pm$ | $Z \parallel b$ | Colorless |  | Perf. ∥ 001 | ? |
| — | Mono. | + | ∥ 001 | $X \parallel c\pm$ | $Z \parallel b$ | Colorless |  | Perf. ∥ 001 | 1.6 |
| — | Mono. | + | ∥ 001 | $X \parallel c\pm$ | $Y \parallel b$ | Z, Y yellow<br>X colorless | $Z>Y>X$ | Perf. ∥ 001 | 1.60 |
| — | Mono. | + | ∥ 001 | $X\wedge c= 0^\circ-7^\circ$ | $Y \parallel b$ | Z, Y brown<br>X yellowish | $Z>Y>X$ | Perf. ∥ 001 | ? |
| — | Mono. | + | ∥ 001 | $X \parallel c\pm$ | $Y \parallel b$ | Z, Y brown or green, X yellow | $Z>Y>X$ | Perf. ∥ 001 | 1.5<br>-1.6 |
| — | Mono. | ± | ∥ 001 | $X\wedge c= -31^\circ$ | $Z \parallel b$ | Colorless |  | Perf. ∥ 001 | ? |

#### g. Birefringence very strong $>0.0445$ $<0.0565$

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n$ |
|---|---|---|---|---|---|---|---|---|---|
| + | Mono. | + | $\parallel c$ | $Z\wedge c= 34^\circ\pm$ | $X \parallel b$ | Colorless |  | ∥ 010 |  |
| + | Mono. | ± | $\parallel c$ | $Z\wedge c= 45^\circ$ | $Y \parallel b$ | Colorless |  | Perf. ∥ 010 |  |
| + | Mono. | ± | $\parallel c$ | $Z\wedge c= 62^\circ$ | $X \parallel b$ | Z, Y colorless<br>X dark blue | $Z=Y<X$ | Perf. ∥ 010 | 1.6 |
| — | Orth.? | + | ∥ 001 | $X \parallel c\pm$ | $Z \parallel b$ | Colorless |  | Perf. ∥ 001 | 1.5 |
| — | Mono. | + | ∥ 001 | $X \parallel c\pm$ | $Z \parallel b$ | Colorless |  | Perf. ∥ 001 | 1.5<br>-1.6 |
| — | Mono. | + | ∥ 001 | $X \parallel c\pm$ | $Y \parallel b$ | Z, Y brown or green, X yellow | $Z>Y>X$ | Perf. ∥ 001 | 1.5<br>-1.6 |
| — | Mono. | + | $\parallel c$ | $Z\wedge c= +32^\circ$ | $X \parallel b$ | Z, Y colorless to greenish yellow<br>X dark blue | $X>Z>Y$ | Perf. ∥ 010 |  |

#### h. Birefringence extreme $>0.0565$

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n$ |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth. | + | $\parallel c$ | $Z \parallel c$ | $X \parallel a$ | Colorless |  | Perf. ∥ 010 | 1.6 |
| + | Orth. | ± | $\parallel c$ | $Y \parallel c$ | $Z \parallel b$ | Colorless |  | None | 1.5 |
| + | Mono. |  |  | $Z\wedge c= -11^\circ$ | $X \parallel b$ | Colorless |  | ∥ 001, 010, 110 | 1.6 |
| — | Orth. | — | $\parallel c$ | $X \parallel c$ | $Z \parallel b$ | Colorless |  | Dist. ∥ 010 | 1.6 |
| — | Orth. | — | $\parallel c$ | $X \parallel c$ | $Z \parallel b$ | Colorless |  | Poor ∥ 110 | 1.6 |
| — | Orth. | — | $\parallel c$ | $X \parallel c$ | $Z \parallel a$ | Colorless |  | Dist. ∥ 110 | 1.6 |

| $n_m$ | $n_p$ | $n_g-n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|
| 1.576 | 1.571 | 0.043 | $2V=42^\circ$ | $\rho<v$ | Anhydrite | $CaSO_4$ |
| 1.589? | 1.539 | 0.035<br>-0.050 | $2E=6^\circ$ to $40^\circ$ | $\rho>v$ | **Talc** | $H_2Mg_3(SiO_3)_4$ |
| 1.58 | ? | 0.041 | $2E=107^\circ\pm$ | $\rho>v$<br>weak | Pyrophyllite | $H_2Al_2(SiO_3)_4$ |
| 1.587<br>-1.593 | 1.557<br>-1.560 | 0.033<br>-0.049 | $2E=70^\circ\pm$ | $\rho>v$<br>weak | **Muscovite** | $H_2(K,Na)Al_3(SiO_4)_3$ |
| 1.60 | ? | Strong | ? | ? | Paragonite | $H_2(Na,K)Al_3(SiO_4)_3$ |
| 1.5975 | 1.56± | 0.037 ± | $2E=70^\circ\pm$ | $\rho>v$ | Lepidolite | $(Li,K)(AlF)Al(SiO_3)_3$ |
| 1.606 | 1.562 | 0.044 | $2E=0^\circ$ to $30^\circ$ | $\rho<v$ | Phlogopite | $(K,H)_3(MgF)_3Mg_3Al(SiO_4)_3$ |
| ? | ? | Strong | $2E=50^\circ\pm$ | $\rho<v$ | Zinnwaldite | Sil. of Al,Fe,Li,K,Na,H |
| 1.574<br>-1.638 | 1.541<br>-1.586 | 0.033<br>-0.060 | $2E=0^\circ$ to $15^\circ$ | $\rho<v$ | **Biotite** | Sil. of Al,Fe,Mg,H |
| ? | ? | ? | $2E=10^\circ\pm$ | $\rho>v$<br>very strong | Glauberite | $Na_2SO_4\cdot CaSO_4$ |

| | | | | | | |
|---|---|---|---|---|---|---|
| ? | ? | ? | $2E=125^\circ\pm$ | $\rho<v$<br>weak | Bobierrite | $Mg_3(PO_4)_2+8H_2O$ |
| 1.52 | ? | ? | $2E=88^\circ$ | $\rho<v$<br>Incl. strong | Hautefeuillite | $(Mg,Ca)_3(PO_4)_2+8H_2O$ |
| 1.605 | 1.5766 | 0.050 | $2E=143^\circ$ | $\rho<v$ | Vivianite | $Fe_3(PO_4)_2+8H_2O$ |
| 1.589? | 1.539 | 0.035<br>-0.050 | $2E=6^\circ$ to $40^\circ$ | $\rho>v$ | **Talc** | $H_2Mg_3(SiO_3)_4$ |
| 1.587<br>-1.593 | 1.557<br>-1.560 | 0.033<br>-0.049 | $2E=70^\circ\pm$ | $\rho>v$<br>weak | **Muscovite** | $H_2(K,Na)Al_3(SiO_4)_3$ |
| 1.579<br>-1.638 | 1.541<br>-1.586 | 0.033<br>-0.060 | $2E=0^\circ$ to $15^\circ$ | $\rho<v$ | **Biotite** | Sil. of Al,Fe,Mg,H |
| ? | ? | ? | $2H=107^\circ$ | ? | Symplesite | $Fe_3(AsO_4)_2+8H_2O$ |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1.5908 | 1.5595 | 0.0716 | $2V=87^\circ$ | $\rho>v$<br>weak | Hambergite | $Be_2(OH)BO_3$ |
| 1.5095 | 1.5043 | 0.071 | $2E=48^\circ$ | ? | Pirssonite | $CaNa_2(CO_3)_2+2H_2O$ |
| 1.5552 | 1.4900 | 0.160 | $2V=84^\circ$ | $\rho<v$<br>weak | Whewellite | $CaC_2O_4+H_2O$ |
| 1.682 | 1.530 | 0.156 | $2E=31^\circ$ | $\rho<v$ | **Aragonite** | $CaCO_3$ |
| 1.670 ± | 1.525 | 0.145 | $2E=10^\circ$ | Weak | Bromlite | $(Ca,Ba)CO_3$ |
| 1.664 | 1.518 | 0.147 | $2E=10^\circ$ | $\rho<v$ | **Strontianite** | $SrCO_3$ |

### 2. Refringence low >1.52 <1.59 (Cont.)

#### c. Birefringence extreme >0.0565 (Cont.)

| SIGN | SYST. | ELONGATION | | | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
| | | Sign | Direc. | Ext. Ang. | | | | | |
| — | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *a* | Colorless | | Dist. ∥ 010 | 1.67 |
| — | Mono. | ± | ∥ *c* | X∧*c*= +65° | Z ∥ *b* | Colorless | | Perf. ∥ 110 | 1.68 |

### 3. Refringence moderate >1.59 <1.66

#### a. Birefringence unknown

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| — | Orth. | + | ∥ 001 | X ∥ *c* | ? | Yellow green in mass | ? | Perf. ∥ 001 | ? |

#### a. Birefringence very weak <0.0035

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| — | Orth.? | + | ∥ *c* | Z ∥ *c* | ? | Green in mass | ? | ? | ? |

#### b. Birefringence weak >0.0035 <0.0095

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth. | + | ∥ *c* | Z ∥ *c* | Y ∥ *b* | Colorless | | Perf. ∥ 110<br>Dist. ∥ 010 | 1.66<br>-1.67 |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | Y ∥ *b* | Colorless | | Perf. ∥ 001 | 1.61<br>-1.63 |
| + | Orth. | + | ∥ 001 | X ∥ *c* | Z ∥ *a* | Colorless | | Perf. ∥ 001<br>Dist. ∥ 110 | 1.63 |
| — | Orth. | ± | ∥ *c* | Y ∥ *c* | X ∥ *b* | Colorless | | ∥ 001 | 1.63 |
| — | Mono. | + | ∥ 001 | X∧*c*= 6°± | Y ∥ *b* | Colorless | | Perf. ∥ 001 | ? |

#### c. Birefringence moderate >0.0095 <0.0185

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth.<br>Ps. Is. | | | Opt. Pl. ∥ 010? | | Colorless | | | 1.67 |
| + | Orth. | | | Z ∥ *c* | Y ∥ *b* | Colorless | | Perf. ∥ 110 | 1.6 |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | Y ∥ *b* | Colorless | | Perf. ∥ 001 | 1.6<br>-1.6 |
| + | Orth. | + | ∥ 001 | X ∥ *c* | Z ∥ *a* | Colorless | | Perf. ∥ 001<br>Perf. ∥ 110 | 1.6 |
| + | Mono. | + | ∥ *c* | Z∧*c*= 2° | Y ∥ *b* | Colorless to yellowish | None | Dist. ∥ 100 | 1.6 |
| + | Mono. | + | ∥ *c* | Z∧*c*= 33°± | Y ∥ *b* | Z yellow green<br>Y brown yellow<br>X pale yellow | Y>Z>X | Perf. ∥ 110 | ? |
| + | Mono. | — | ∥ 001 | Z ∥ *c*± | Y ∥ *b* | Z colorless<br>Y, X pale green | Z<Y<X | Perf. ∥ 001 | 1.5 |
| — | Orth. | | | X ∥ *b* | Z ∥ *a* | Colorless | | Poor ∥ 010 | 1.6 |
| — | Orth. | — | ∥ *c* | X ∥ *c* | Y ∥ *b* | Z, Y colorless<br>X rose red | X>Y>Z | Dist. ∥ 110 | 1.6 |
| — | Mono. | + | ∥ 001 | X ∥ *c*± | Y ∥ *b* | Z, Y yellow<br>X colorless | Z=Y>X | Perf. ∥ 001 | 1.6 |
| — | Mono.? | + | ∥ 001 | X ∥ *c*± | ? | Z, Y green or pink. X colorless | Z=Y>X | Perf. ∥ 001 | |

| $n_m$ | $n_p$ | $n_g-n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|
| 1.676 | 1.529 | 0.148 | $2E=26°$ | $\rho>v$ | **Witherite** | $BaCO_3$ |
| 1.684 | 1.525 | 0.161 | $2E=24°$ | $\rho>v$ weak | Barytocalcite | $BaCa(CO_3)_2$ |
| | | | | | | |
| 1.62? | ? | ? | $2E=18°\pm$ | ? | Uranocircite | $Ba(UO_2)_2(PO_4)_2+8H_2O$ |
| | | | | | | |
| 1.59 | ? | Weak | $2V$ small | ? | Garnierite | Sil. of Mg,Ni,H |
| | | | | | | |
| 1.659 -1.669 | 1.656 -1.665 | 0.009 | $2V=70°$ to 80° | $\rho>v$ | **Enstatite** | $MgSiO_3$ |
| 1.610 -1.631 | 1.607 -1.629 | 0.008 -0.010 | $2E=84°$ to 125° | $\rho>v$ dist. | Topaz | $(AlF_2)AlSiO_4$ |
| 1.623 | 1.622 | 0.009 | $2V=51°$ | $\rho<v$ | Celestite | $SrSO_4$ |
| 1.6337 | 1.6317 | 0.0046 | $2V=88°$ | $\rho<v$ very strong | Danburite | $CaB_2(SiO_4)_2$ |
| 1.64 -1.65 | ? | 0.009 ± | $2E=80°$ to 125° | $\rho<v$ | Margarite | $H_2CaAl_4Si_2O_{12}$ |
| | | | | | | |
| 1.667 | 1.662 | 0.011 | $2V=90°\pm$ | ? | Boracite | $Mg_7Cl_2B_{16}O_{30}$ |
| 1.6125 | 1.609 | 0.010 | $2V=70°$ | $\rho<v$ | Stokesite | $H_4Ca(Si,Sn)_4O_{11}$ |
| 1.610 -1.631 | 1.607 -1.629 | 0.008 -0.010 | $2E=84°$ to 125° | $\rho>v$ dist. | Topaz | $(AlF_2)AlSiO_4$ |
| 1.637 | 1.636 | 0.011 | $2V=36°\pm$ | $\rho<v$ | **Barite** | $BaSO_4$ |
| 1.6490 | 1.6455 | 0.012 | $2V=74°\pm$ | $\rho>v$ dist. | Mosandrite | Sil. of Ce,Ca,Na,F |
| ? | ? | 0.014 ± | $2V$ large | ? | **Hornblende** | Sil. of Fe,Al,Mg,Ca,Na |
| 1.588 | 1.585 | 0.011 | $2E=0°$ to 70° | $\rho<v$ | **Clinochlore** | Sil. of Al,Mg,Fe,H |
| 1.6616 | 1.6505 | 0.017 | $2V=38°$ | $\rho>v$ | Monticellite | $MgCaSiO_4$ |
| 1.638 | 1.632 | 0.011 | $2V=84°\pm$ | ? | Andalusite | $Al_2SiO_5$ |
| 1.657 | 1.646 | 0.012 | $2E=10°\pm$ | $\rho<v$ weak | Seybertite | Sil. of Al,Mg,Ca,H |
| ? | ? | 0.014 | $2E=0°+$ | ? | **Delessite** | Sil. of Al,Mg,Fe,H |

### 3. Refringence moderate >1.59 <1.66 (Cont.)

#### c. Birefringence moderate >0.0095 <0.0185 (Cont.)

| SIGN | SYST. | ELONGATION |  |  | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | *n* |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Sign | Direc. | Ext. Ang. |  |  |  |  |  |
| — | Mono. | + | ∥ 001 | X ∥ *c*± | Y ∥ *b* | Z, Y green<br>X brown | ? | Perf. ∥ 001 | 1.6 |
| — | Mono. | + | ∥ *c* | Z ∥ *c*= +5°± | Y ∥ *b* | Z dark blue<br>Y violet blue<br>X yellowish | Z>Y>X | Perf. ∥ 110 | 1.6 |
| — | Mono. | ± | ∥ *b* | X∧*c*= —32° | Y ∥ *b* | Colorless |  | Perf. ∥ 100<br>Dist. ∥ 001 | 1.6 |

#### d. Birefringence rather strong >0.0185 <0.0275

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | *n* |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth. | + | ∥ *c* | Z ∥ *c* | Y ∥ *b* | Colorless |  | Perf. ∥ 010 | 1.6 |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *b* | Colorless |  | Perf. ∥ 110 | 1.6 |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *a* | Colorless |  | Perf. ∥ 110 | 1.6 |
| + | Orth.? | +? | ∥ *c*? | Z ∥ *c*? | ? | Colorless |  | ? |  |
| + | Mono. | + | ∥ *c* | Z∧*c*= +25°± | Y ∥ *b* | Colorless |  | Perf. ∥ 110 | 1.6 |
| + | Mono. | + | ∥ *c* | Z∧*c*= +15°-25° | Y ∥ *b* | Z green, blue or pink<br>Y, X greenish | Z>Y>X | Perf. ∥ 110 | 1.6 |
| + | Mono. | + | ∥ *c* | X∧*c*= +41° | Y ∥ *b* | Colorless or green and blue | Absent or ? | Perf. ∥ 010 | 1.6 |
| +? | Mono. | — | ∥ *b* | Z∧*c*= 13°± | X ∥ *b* | Colorless to pale yellow | Z>Y>X | Perf. ∥ 001<br>Dist. ∥ 100 |  |
| + | Tri. | ± | ∥ *c* | Ext. on 100=30° | Ext. on 010=25° | Colorless |  | Perf. ∥ 010 |  |
| — | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *a* | Colorless |  | Perf. ∥ 110 | 1.6 |
| — | Orth. | + | ∥ *c* | Z ∥ *c* | ? | Colorless, or Z colorless<br>Y, X yellow | Z<Y=X | ∥ *c* |  |
| — | Orth. | — | ∥ 001 | Z ∥ *c* | X ∥ *a* | Colorless |  | ∥ 001, 110, 010, 100 | 1. |
| — | Mono. | + | ∥ *c* | Z∧*c*= +16° to + 18° | Y ∥ *b* | Colorless |  | Perf. ∥ 110 | 1. |
| — | Mono. | + | ∥ *c* | Z∧*c*= +15° | Y ∥ *b* | Z green<br>Y green yellow<br>X yellow | Z>Y>X | Perf. ∥ 110 | 1. |
| — | Mono. | + | ∥ *c* | Z∧*c*= +17° to + 20° | Y ∥ *b* | Z yellow<br>Y colorless<br>X brown | X>Z>Y | Perf. ∥ 110 | 1. |
| — | Mono. | + | ∥ *c* | Z∧*c*= +15°± | Y ∥ *b* | Z brown yellow<br>Y,X pale yellow | Z>Y=X | Perf. ∥ 110 |  |
| — | Mono. | + | ∥ *c* | Z∧*c*= +15° to +25° | Y ∥ *b* | Z green or yellow. Y green or brown. X yellow or brown Rarely colorless | Z>Y>X | Perf. ∥ 110 | 1. |
| — | Mono. | + | ∥ *c* | Z∧*c*= +4° to +6° | Y ∥ *b* | Z dark blue<br>Y violet blue<br>X yellowish | Z>Y>X | Perf. ∥ 110 | 1. |
| — | Mono.? | + | ∥ 001 | X ∥ *c*± | ? | Green to yellow | ? | Perf. ∥ 001 |  |
| — | Tri. |  |  | X ∥ 001 and $1\bar{1}0$ |  | Colorless |  | Perf. ∥ 001<br>Dist. ∥ $1\bar{1}0$ | 1. |

| $n_m$ | $n_p$ | $n_g - n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|
| 1.660 | 1.649 | 0.012 | $2E=25°\pm$ | $\rho<v$ weak | Xanthophyllite | Sil. of Al,Mg,Ca,H |
| 1.638 -1.644 | 1.621 | 0.018 -0.022 | $2V=42°$ to 50° | $\rho<v$ | **Glaucophane** | $NaAlSi_2O_6$ with $(Fe,Mg)SiO_3$ |
| 1.633 | 1.621 | 0.014 | $2E=70°$ | $\rho<v$ | Wollastonite | $CaSiO_3$ |

| $n_m$ | $n_p$ | $n_g - n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|
| 1.658 | 1.656 | 0.020 | $2V=30°\pm$ | $\rho>v$ | **Sillimanite** | $Al_2SiO_5$ |
| 1.618 | 1.615 | 0.020 | $2E=80°$ | $\rho>v$ strong | Calamine | $(ZnOH)_2SiO_3$ |
| 1.642 | 1.633 | 0.025 | $2V=84°\pm$ | $\rho<v$ | **Anthophyllite** | $(Mg,Fe)SiO_3$ |
| ? | ? | 0.020 | $2E=50°\pm$ | ? | Ktypeite | $CaCO_3$ |
| 1.669 | 1.651 | 0.026 | $2V=54°$ to 60° | $\rho<v$ | Spodumene | $LiAl(SiO_3)_2$ |
| 1.620 | 1.613 | 0.019 | $2V=59°\pm$ | $\rho>v$ | Pargasite | Sil. of Al,Fe,Mg,Ca,Na |
| 1.655 | 1.652 | 0.019 | $2E=88°$ | $\rho>v$ | Euclase | $Be(AlOH)SiO_4$ |
| 1.65 | ? | 0.026 | $2V=90°\pm$ | ? | Rosenbuschite | Sil. of Ca,Ti,Zr,Na,F |
| 1.62 | ? | Strong | ? | ? | Parahopeite | $Zn_3P_2O_8+4H_2O$ |
| 1.636 | 1.623 | 0.021 -0.023 | $2V=78°\pm$ | $\rho>v$ | Gedrite | $(Mg,Fe)SiO_3$ with $(Mg,Fe)Al_2SiO_6$ |
| 1.63 | ? | 0.022 | $2V=60°$ | ? | Carpholite | $H_4MnAl_2Si_2O_{10}$ |
| 1.593 | 1.588 | 0.023 | $2V=75°\pm$ | $\rho>v$ | Bertrandite | $H_2Be_4Si_2O_9$ |
| 1.623 | 1.609 | 0.026 | $2V=85°\pm$ | $\rho<v$ | **Tremolite** | $CaMg_3(SiO_3)_4$ |
| 1.627 | 1.611 | 0.025 | $2V=78°\pm$ | $\rho<v$ | **Actinolite** | $Ca(Mg,Fe)_3(SiO_3)_4$ |
| 1.63 | 1.62 | 0.024 | $2V=80°\pm$ | $\rho<v$ | Richterite | $(K_2Na_2,Mg,Ca,Mn)SiO_3$ |
| 1.638 | ? | 0.022± | $2V=78°\pm$ | $\rho<v$ | Cummingtonite | $(Fe,Mg)SiO_3$ |
| 1.642 | 1.629 | 0.024 | $2V=84°\pm$ | $\rho<v$ | **Hornblende** | Sil. of Al,Fe,Mg,Ca,Na |
| 1.638 -1.644 | 1.621 | 0.018 -0.022 | $2V=42°$ to 50° | $\rho<v$ | **Glaucophane** | $NaAlSi_2O_6$ with $(Fe,Mg)SiO_3$ |
| 1.61 | ? | 0.020± | $2E=0°$ to 40° | ? | Glauconite | $KFe(SiO_3)_2+nH_2O$ |
| 1.593 | 1.578 | 0.019 | $2V=52°\pm$ | $\rho<v$ Incl. cross'd | Amblygonite See also Montebrazite | $Li[Al(F,OH)]PO_4$ |

3. Refringence moderate >1.59 <1.66 (Cont.)

e. Birefringence strong >0.0275 <0.0355

| SIGN | SYST. | ELONGATION |  |  | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Sign | Direc. | Ext. Ang. |  |  |  |  |  |
| + | Hex? | — | ∥ 0001 | Z ∥ | X ∥ 10$\bar{1}$0 | Colorless to yellow |  | Perf. ∥ 10$\bar{1}$0 | 1.62 |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | Y ∥ *b* | Colorless |  | Dist. ∥ 001 | 1.64 |
| + | Orth. | ± | ∥ *c* | Y ∥ *c* | X ∥ *b* | Colorless |  | Poor ∥ 010 | ? |
| + | Orth. | —<br>or± | ∥ *a*<br>or ∥ *c* | X ∥ *a* | Y ∥ *c* | Colorless or<br>Z, Y pale yellow<br>X golden " | X>Z>Y | Poor ∥ 001 | ? |
| + | Mono. |  |  | X∧*a*=<br>7° to 12° | Z ∥ *b* | Colorless or Z, Y<br>pale yellow<br>X golden " | X>Z>Y | Poor ∥ 001 | 1.69 |
| + | Mono.? | + | ∥ *c* | X∧*c*=<br>+33°± | Y ∥ *b* | Colorless to green | ? | Perf. ∥ 110 | ? |
| + | Mono. | ± | ∥ *c* | Z∧*c*=<br>83° | X ∥ *b* | Colorless |  | Perf. ∥ 010<br>Dist. ∥ 001 | 1.61 |
| + | Mono. | — | ∥ 010? | X∧*a*=<br>47° | Z ∥ *b* | Colorless to yellow | ? | Poor ∥ 001? | ? |
| + | Mono. | — | ∥ 010 | X∧*a*=<br>26° to 30° | Z ∥ *b* | Colorless or Z, Y<br>pale yellow<br>X golden " | X>Z>Y | Poor ∥ 001 | 1.63 |
| — | Mono. | — | ∥ *a* | X∧*a*=<br>+2° | Z ∥ *c* | Colorless |  |  | 1.62 |

f. Birefringence strong >0.0355 <0.0445

|  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth. | —<br>or± | ∥ *a*<br>or ∥ *c* | X ∥ *a* | Y ∥ *c* | Colorless or Z, Y<br>pale yellow<br>X golden " | X>Z>Y | Poor ∥ 001 | ? |
| + | Orth. | — | ∥ 001 | Z ∥ *c* | X ∥ *a* | Colorless |  | Perf. ∥ 001<br>Perf. ∥ 010<br>Dist. ∥ 100 | 1.61 |
| + | Mono. | + | ∥ *b* | Z ∥ *b* | X ∥ *a*± | Colorless |  | Perf. ∥ 001<br>Perf. ∥ 100 | ? |
| — | Orth. |  |  | X ∥ *a* | Z ∥ *b* | Z pale blue green.<br>Y colorless<br>X green blue | X>Z>Y | ∥ 100, 010 | 1.63 |
| — | Mono. | + | ∥ *c* | Z∧*c*=<br>1° to 4° | Y ∥ *b* | Colorless |  | None | 1.67 |
| — | Mono. | + | ∥ 001 | X ∥ *c*± | Z ∥ *b* | Colorless |  | Perf. ∥ 001 | 1.59<br>-1.60 |
| — | Mono. | + | ∥ 001 | X ∥ *c*± | Z ∥ *b* | Colorless |  | Perf. ∥ 001 | 1.60 |
| — | Mono. | + | ∥ 001 | X ∥ *c*± | Y ∥ *b* | Z, Y yellow<br>X colorless | Z>Y>X | Perf. ∥ 001 | 1.606 |
| — | Mono. | + | ∥ 001 | X ∥ *c*± | Y ∥ *b* | Z, Y brown or green<br>X yellow | Z>Y>X | Perf. ∥ 001 | 1.57<br>-1.63 |
| — | Mono. | ± | ∥ 001 | X∧*c*=<br>- 31° | Z ∥ *b* | Colorless |  | Perf. ∥ 001 | ? |
| — | Mono. | ± | ∥ *c* | Y∧*c*=<br>+3° | Z ∥ *b* | Colorless |  | Dist. ∥ 010 | 1.68 |
| — | Mono. | — | ∥ *c* | X∧*c*=<br>—10° | Y ∥ *b* | Z, Y azure blue<br>X colorless | Z=Y>X | Prismatic poor | 1.63 |

# axial Minerals (Cont.)

| | $n_m$ | $n_p$ | $n_g-n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|---|
| 9 | ? | 1.599 | 0.030 | Uniaxial or $2V$ small | ? | Catapleiite | $H_4(Na_2,Ca)ZrSi_3O_{11}$ |
| 9 | 1.626 | 1.616 | 0.033 | $2E=123°\pm$ | $\rho>v$ | Prehnite | $H_2Ca_2Al_2(SiO_4)_3$ |
| | 1.659 | ? | 0.034 ± | $2V=86°$ | $\rho<v$ | Forsterite | $Mg_2SiO_4$ |
| | 1.643 | ? | 0.032<br>-0.038 | $2V=68°$ | $\rho>v$ | Humite | $[Mg(F,OH)]_2Mg_5(SiO_4)_3$ |
| 0 | 1.670 | 1.658 | 0.032 | $2V=76°$ | $\rho>v$<br>crossed | Clinohumite | $[Mg(F,OH)]_2Mg_7(SiO_4)_4$ |
| | 1.654 | ? | 0.029 | $2V=70°$ | $\rho<v$ | Jadeite | $NaAl(SiO_3)_2$ |
| 40 | 1.592 | 1.586 | 0.028 | $2E=95°$ | $\rho<v$ | Colemanite | $Ca_2B_6O_{11}+5H_2O$ |
| | 1.6703 | ? | ? | $2K=80°$ | ? | Prolectite | $[Mg(F,OH)]_2MgSiO_4$ |
| 9 | 1.619 | 1.607 | 0.032 | $2V=80°$ | $\rho>v$<br>crossed | Chondrodite | $[Mg(F,OH)]_2Mg_3(SiO_4)_2$ |
| 1 | 1.612 | 1.592 | 0.029 | $2E=121°$ to $128°$ | $\rho>v$ | Herderite | $[Ca(F,OH)]BePO_4$ |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1.643 | ? | 0.032<br>-0.038 | $2V=68°$ | $\rho>v$ | Humite | $[Mg(F,OH)]_2Mg_5(SiO_4)_3$ |
| 4 | 1.576 | 1.571 | 0.043 | $2V=42°$ | $\rho<v$ | Anhydrite | $CaSO_4$ |
| | 1.61 | ? | 0.038 | $2V=60°$ | $\rho>v$<br>strong | Pectolite | $HNaCa_2(SiO_3)_3$? |
| 35 | 1.6360 | 1.6018 | 0.037 | $2V=37°$ | $\rho<v$<br>very strong | Grandidierite | Sil. of Al,Fe,Mg,Na,H |
| 0 | 1.653 | 1.626 | 0.044 | $2V=75°$ | $\rho>v$ | Datolite | $Ca(BOH)SiO_4$ |
| 0<br>9 | 1.587<br>-1.593 | 1.557<br>-1.560 | 0.033<br>-0.049 | $2E=70°\pm$ | $\rho>v$<br>weak | **Muscovite** | $H_2(K,Na)Al_3(SiO_4)_3$ |
| 47 | 1.5975 | 1.56± | 0.037 ± | $2E=70°\pm$ | $\rho>v$<br>weak | Lepidolite | $(Li,K)(AlF)Al(SiO_3)_3$ |
| - | 1.606 | 1.562 | 0.044 | $2E=0°$ to $30°$ | $\rho<v$<br>weak | Phlogopite | $(K,H)_3(MgF)_3Mg_3Al(SiO_4)_3$ |
| 4<br>8 | 1.574<br>-1.638 | 1.541<br>-1.586 | 0.033<br>-0.060 | $2E=0°$ to $30°$ | $\rho<v$<br>weak | **Biotite** | Sil. of Fe,Al,Mg,H |
| | ? | ? | ? | $2E=10°$ | $\rho>v$<br>very strong | Glauberite | $Na_2SO_4 \cdot CaSO_4$ |
| 78 | 1.6609 | 1.6445 | 0.043 | $2V=77°$ | $\rho>v$<br>dist. | Leucosphenite | Sil. of Ti,Ba,Na |
| 9 | 1.632 | 1.603 | 0.036 | $2E=134°\pm$ | $\rho<v$ | Lazulite | $(Mg,Fe)(AlOH)_2(PO_4)_2$ |

### 3. Refringence moderate >1.59 <1.66 (Cont.)

#### g. Birefringence very strong >0.0445 <0.0565

| SIGN | SYST. | ELONGATION |  |  | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Sign | Direc. | Ext. Ang. |  |  |  |  |  |
| + | Mono. | ± | ∥ *c* | $Z \wedge c = 62^\circ$ | X ∥ *b* | Z, Y colorless<br>X dark blue | Z=Y<X | Perf. ∥ 010 | 1.62 |
| — | Mono. | + | ∥ 001 | X ∥ *c*± | Z ∥ *b* | Colorless | - | Perf. ∥ 001 | 1.59<br>-1.60 |
| — | Mono. | + | ∥ 001 | X ∥ *c*± | Y ∥ *b* | Z, Y brown or green, X yellow | Z>Y>X | Perf. ∥ 001 | 1.57<br>-1.63 |
| — | Mono. | + | ∥ *c* | $X \wedge c = -35^\circ$ | X ∥ *b* | Green in mass | ? | Perf. ∥ 010 | ? |
| — | Mono. | ? | ∥ *c* | ? | X ∥ *b* | Green in mass | Pleoch. | Perf. ∥ 010 | ? |

#### h. Birefringence extreme >0.0565

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *a* | Colorless |  | Perf. ∥ 010 | 1.63 |
| + | Mono. |  |  | $Z \wedge c = -11^\circ$ | X ∥ *b* | Colorless |  | ∥ 001, 010, 110 | 1.64 |
| + | Mono. | + | ∥ *c* | $Z \wedge c = -12^\circ$ | Y ∥ *b* | Emerald green in mass | ? | Perf. ∥ 001 | 1.71 |
| — | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *b* | Colorless |  | Dist. ∥ 010 | 1.68 |
| — | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *b* | Colorless |  | Poor ∥ 110 | 1.67 |
| — | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *a* | Colorless |  | Dist. ∥ 110 | 1.66 |
| — | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *a* | Colorless |  | Dist. ∥ 110 | 1.67 |
| — | Mono. | + | ∥ *c* | $Z \wedge c = -31^\circ$ | X ∥ *b* | Red, green blue | Pleoch. | Perf. ∥ 010 | 1.69 |
| — | Mono. | + | ∥ *c* | $Z \wedge c = -41^\circ$ | Y ∥ *b* | Blue in mass | ? | Perf. ∥ 010<br>Dist. ∥ 011 | 1.66 |
| — | Mono. | + | ∥ 001 | X ∥ *c*± | Y ∥ *b* | Z, Y brown or green, X yellow | Z>Y>X | Perf. ∥ 001 | 1.57<br>-1.63 |
| — | Mono. | ± | ∥ *c* | $X \wedge c = +65^\circ$ | Z ∥ *b* | Colorless |  | Perf. ∥ 110 | 1.68 |

### 4. Refringence high >1.66 <1.75

#### a. Birefringence unknown

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth. | + | ∥ 010 | Z ∥ *c* | X ∥ *b* | Colorless |  | Perf. ∥ 010 | 1.67 |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *a* | Z colorless<br>Y carmine<br>X pink | Y>X>Z | Perf. ∥ 010 | ? |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *b* | Green | Strong |  | ? |
| + | Mono. | + | ∥ *c*? | $Z \wedge c = +39^\circ$ | ? | Colorless |  | None | ? |
| — | Rhom.? |  |  | X ∥ *c*± | ? | Brown | ? | Perf. ∥ 0001 | 1.72 |
| — | Orth. | + | ∥ 001 | X ∥ *c* | Z ∥ *a* | Green to blue in mass | ? | Perf. ∥ 010 | ? |
| — | Orth. | ± | ∥ *c* | Y ∥ *c* | X ∥ *b* | Olive green in mass | ? | Poor ∥ 100<br>Poor ∥ 010 | ? |

## iaxial Minerals (Cont.)

| | $n_m$ | $n_p$ | $n_g-n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|---|
| 67 | 1.605 | 1.5766 | 0.050 | $2E=143°$ | $\rho<v$ | Vivianite | $Fe_3(PO_4)_2+8H_2O$ |
| 0<br>9 | 1.587<br>-1.593 | 1.557<br>-1.560 | 0.033<br>-0.049 | $2E=70°\pm$ | $\rho>v$ weak | **Muscovite** | $H_2(K,Na)Al_3(SiO_4)_3$ |
| 4<br>8 | 1.574<br>-1.638 | 1.541<br>-1.586 | 0.033<br>-0.060 | $2E=0°$ to $30°$ | $\rho<v$ weak | **Biotite** | Sil. of Al,Fe,Mg,H |
| | ? | ? | ? | $2H=110°\pm$ | $\rho>v$ strong | Cabrerite | $(Ni,Mg)_3(AsO_4)_2+8H_2O$ |
| | 1.63 | ? | ? | $2H=105°\pm$ | ? | Annabergite | $Ni_3(AsO_4)_2+8H_2O$ |
| 11 | 1.5908 | 1.5595 | 0.0716 | $2V=87°$ | $\rho>v$ weak | Hambergite | $Be_2(OH)BO_3$ |
| 97 | 1.5552 | 1.4900 | 0.1597 | $2V=84°$ | $\rho<v$ weak | Whewellite | $CaC_2O_4+H_2O$ |
| 43 | 1.6555 | 1.6491 | 0.0652 | $2V=37°$ | $\rho<v$ strong | Natrochalcite | $Na_2Cu_4(OH)_2(SO_4)_3+2H_2O$ |
| 6 | 1.682 | 1.530 | 0.156 | $2E=31°$ | $\rho<v$ | **Aragonite** | $CaCO_3$ |
| ± | 1.670 ± | 1.525 | 0.145 | $2E=10°$ | Weak | Bromlite | $(Ca,Ba)CO_3$ |
| 5 | 1.664 | 1.518 | 0.147 | $2E=10°$ | $\rho<v$ | **Strontianite** | $SrCO_3$ |
| 7 | 1.676 | 1.529 | 0.148 | $2E=26°$ | $\rho>v$ | **Witherite** | $BaCO_3$ |
| 86 | 1.6614 | 1.6263 | 0.0723 | $2H=105°$ | $\rho>v$ weak | Erythrite | $Co_3(AsO_4)_2+8H_2O$ |
| 13 | 1.5775 | 1.5437 | 0.0576 | $2V=79°$ | $\rho<v$ weak | Kröhnkite | $Na_2Cu(SO_4)_2+2H_2O$ |
| 4<br>8 | 1.574<br>-1.638 | 1.504<br>-1.589 | 0.033<br>-0.085 | $2E=0°$ to $40°$ | $\rho<v$ | **Biotite** | Sil. of Al,Fe,Mg,H |
| 6 | 1.684 | 1.525 | 0.161 | $2E=24°$ | $\rho>v$ weak | Barytocalcite | $BaCa(CO_3)_2$ |
| | ? | ? | ? | $2V$ large | $\rho>v$ weak | Haidingerite | $HCaAsO_4+H_2O$ |
| | 1.7315 | ? | ? | $2E=126°$ | $\rho>v$ strong | Phosphosiderite | $FePO_4+3\frac{1}{2}H_2O$ |
| | 1.70 | ? | ? | $2E=61°$ | ? | Euchroite | $Cu_2(OH)AsO_4+3H_2O$ |
| | 1.67 | ? | ? | $2E=107°$ | $\rho>v$ | Adelite | $HCaMgAsO_5$ |
| 23 | ? | ? | ? | Uniaxial or $2V$ small | ? | Hematolite | $(Al,Mn)AsO_4 \cdot 4Mn(OH)_2$ |
| | 1.70 | ? | ? | $2V$ large | ? | Tyrolite | $Cu_5(OH)_4(AsO_4)_2+7H_2O$ |
| | 1.742 | ? | ? | $2V=81°$ | $\rho>v$ strong | Libethenite | $Cu(CuOH)PO_4$ |

### 4. Refringence high >1.66 <1.75 (Cont.)

a. Birefringence very weak <0.0035

| SIGN | SYST. | ELONGATION | | | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
| | | Sign | Direc. | Ext. Ang. | | | | | |
| — | Mono. | ± | ∥ *b* | Y ∥ *b* | $X\wedge c = +6^\circ \pm$ | Z, Y brown<br>X paler brown | Z>Y>X | Traces | ? |
| b. Birefringence weak >0.0035 <0.0095 | | | | | | | | | |
| + | Orth. | | | Z ∥ *c* | X ∥ *a* | Colorless | | Traces | 1.75 |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *a* | Colorless | | Perf. ∥ 110 | 1.66 |
| + | Orth.<br>(β-Zoisite has Y ∥ *c*, X ∥ *b*) | — | ∥ *c* | X ∥ *c* | Z ∥ *a* | Colorless<br>(Thulite is pink) | | Perf. ∥ 010 | 1.70 |
| + | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *a* | Colorless | | | 1.68 |
| + | Mono. | ± | ∥ *b* | $Z\wedge c = 2^\circ$ | Y ∥ *b* | Colorless | | Dist. ∥ 001 | 1.72 |
| + | Mono. | — | ∥ *c* | $X\wedge c = -5^\circ$ | Y ∥ *b* | Z yellow green<br>Y blue<br>X dark blue | X>Y>Z | Perf. ∥ 110 | >1.68 |
| + | Mono.? | — | ∥ 001? | Z ∥ *c* ±? | ? | Z blue, Y, X yellow or green to colorless | Z>Y=X | | ? |
| + | Mono.? | — | ∥ 001 | $Z\wedge c = 3^\circ$ to $20^\circ$ | Y ∥ *b* ± | Z green yellow<br>Y indigo blue<br>X olive green | Y>X>Z | Perf. ∥ 001 | ? |
| + | Tri. | ± | ∥ *c* | $Z\wedge c = 45^\circ$ | Y ∥ *b* ± | Z, Y dark brown<br>X clear brown | Z>Y>X | Perf. ∥ 110 | Li |
| ± | Orth. | —<br>Variable | ∥ *c* | X ∥ *c* | Z ∥ *b* | Greenish or bluish in mass | ? | Perf. ∥ 001<br>Dist. ∥ 010 | 1.691 |
| — | Mono. | ± | ∥ 010 | $Z\wedge c = -8^\circ$ | Y ∥ *b* | Z, Y pale blue or green.<br>X colorless | | | 1.711 |
| — | Tri. | | | X ⊥ 011 ± | | Z, X colorless<br>Y violet to colorless | None or Y>X=Z | Dist. ∥ 010<br>Dist. ∥ 1$\bar{1}$2<br>Dist. ∥ 1$\bar{3}$0 | 1.681 |
| c. Birefringence moderate >0.0095 <0.0185 | | | | | | | | | |
| + | Orth.<br>Ps. Is. | | | Z ∥ *c*? | X ∥ *b* ? | Colorless | | Traces | 1.67 |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *a* | Colorless or nearly so | | Perf. ∥ 110 | 1.67 |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *b* | Z golden yellow<br>Y pale yellow<br>X colorless | Z>Y>X | Dist. ∥ 010 | 1.74 |
| + | Orth. | ± | ∥ *c* | Y ∥ *c* | Z ∥ *a* | Colorless | | Prismatic | 1.69 |
| + | Orth. | ± | ∥ *c* | Y ∥ *c* | X ∥ *a* | Z, X pink<br>Y yellow | Z>Y=X | Perf. ∥ 001<br>Poor ∥ 010 | 1.68 |
| + | Mono. | ± | ∥ *c* | $Y\wedge c = 7^\circ$ | X ∥ *b* | Colorless or nearly so | None or weak | Dist. ∥ 100 | 1.68 |
| + | Mono. | ±? | ∥ *b*? | Y ∥ *b* ? | X ∥ *c* ±? | Colorless or nearly so | | Dist. ∥ 001 | 1.7 |
| + | Mono. | ± | ∥ *c* | $Z\wedge c = +45^\circ$ to $+48^\circ$ | Y ∥ *b* | Z greenish<br>Y pale green<br>X yellow green | Weak Z>Y>X | Perf. ∥ 110 | 1.7 |
| + | Tri. | ? | ∥ *c* | Ext. on 010 = 4° | Z ⊥ 010 ± | Colorless or nearly so | None or weak | Poor ∥ 010<br>Poor ∥ 100 | |

## axial Minerals (Cont.)

| $n_m$ | $n_p$ | $n_g-n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|
| 1.68<br>-1.70 | ? | 0.000<br>-0.032 | $2V=68°$ | Strong | Allanite | Sil. of Al,Fe,Ce,Ca,H |
| 1.748 | 1.747 | 0.009 | $2E=85°$ | $\rho>v$ | Chrysoberyl | $BeAl_2O_4$ |
| 1.659 | 1.656 | 0.009 | $2V=70°$ to 90° | $\rho>v$ | **Enstatite** | $MgSiO_3$ |
| 1.699 | 1.697 | 0.005 | $2V=51°\pm$ | $\rho<v$ strong | **Zoisite** | $H_2Ca_4Al_6Si_6O_{26}$ |
| ? | 1.6782 | 0.0049 | $2E=90°$ | $\rho<v$ | Harstigite | $H_7(Ca,Mn)_{12}Al_3(SiO_4)_{10}$ |
| 1.7195 | 1.7176 | 0.0056 | $2V=82°$ | $\rho>v$ strong | Clinozoisite | $H_2Ca_4Al_6Si_6O_{26}$ |
| ? | <1.687 | 0.005 | $2V$ large | Strong | Riebeckite | $2NaFeSi_2O_6 \cdot FeSiO_3$ |
| 1.7± | ? | Weak | $2V$ large | ? | Serendibite | Sil. of Al,Be,Mg,Ca,Fe |
| 1.741 | ? | 0.007<br>-0.016 | $2E=55°$ to 120° | $\rho>v$ strong | Chloritoid | $H_2FeAl_2SiO_7$ |
| ke hornblende | | 0.0064 | $2E=60°\pm$ | ? | Ænigmatite | Sil. of Ti,Al,Fe,Na |
| 1.684 | 1.683 | 0.008± | $2E=0°$ to 60° | $\rho>v$ very strong | Triphylite | $Li(Fe,Mn)PC_4$ |
| 1.7088 | 1.7055 | 0.0057 | $2V=69°$ | $\rho<v$ Incl. | Sapphirine | $Mg_5Al_{12}Si_2O_{27}$ |
| 1.678 | 1.672 | 0.009 | $2V=72°\pm$ | $\rho<v$ Incl. Horiz. | Axinite | Sil. of Al,B,Ca,Fe,H |
| 1.6670 | 1.6622 | 0.0108 | $2V=90°-$ | ? | Boracite | $Mg_7Cl_2B_{16}O_{30}$ |
| 1.6658 | 1.6607 | 0.0108 | $2V=70°$ to 90° | $\rho>v$ | **Enstatite** | $MgSiO_3$ |
| 1.741 | 1.736 | 0.010<br>-0.015 | $2V=88°\pm$ | $\rho>v$ | Staurolite | $HFeAl_5Si_2O_{13}$ |
| 1.685 | 1.68± | 0.014 | $2V=86°$ | $\rho>v$ | Barylite | $Ba_4Al_4Si_7O_{24}$ |
| 1.679 | 1.676 | 0.011 | $2V=55°$ to 65° | $\rho<v$ very strong | Lithiophilite | $Li(Mn,Fe)PO_4$ |
| 1.6682 | 1.6654 | 0.016 | $2V=74°$ | $\rho<v$ strong | Rinkite | Sil. of Ti,Ca,Ce,Na,F |
| 1.7291 | 1.7238 | 0.005<br>-0.020 | $2V=90°\pm$ | $\rho<v$ | Fouquéite | $H_2Ca_4Al_6Si_6O_{26}$ |
| 1.7366 | 1.7320 | 0.0185 | $2V=60°$ | $\rho>v$ | Hedenbergite | $(Ca,Fe)SiO_3$ |
| 1.7± | ? | 0.012 | $2V$ large | ? | Hainite | Sil. of Na,Ca,Ce,Ti,Zr? |

4. Refringence high >1.66 <1.75 (Cont.)

c. Birefringence moderate >0.0095 <0.0185 (Cont.)

| SIGN | SYST. | ELONGATION | | | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
| | | Sign | Direc. | Ext. Ang. | | | | | |
| + | Tri. | ± | ∥ *c* | Ext. on 100=65° | Ext. on 010=75° | Colorless or nearly so | None or weak | Poor ∥ 110<br>Poor ∥ 1̄10 | ? |
| — | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *a* | Z green, Y red yellow, X red | X>Y>Z | Perf. ∥ 110 | 1.70<br>-1.72 |
| — | Orth. | — | ∥ *c* | X ∥ *c* | Y ∥ *a* | Colorless or yellow | | Prismatic | 1.68 |
| — | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *a* | Z, Y colorless X blue, pink, green | Z=Y<X | Dist. ∥ 100 | 1.68 |
| — | Mono. | ± | ∥ *c* | X⊥*c*± | Z ∥ *b* | Pink in mass | ? | | 1.74 |
| — | Mono. | ± | ∥ *b* | Y ∥ *b* | X∧*c*= —3°± | Z yellow green Y blue to green yellow, X yellow or green | Y>Z>X | Dist. ∥ 001 | ? t<br>1.76 |
| — | Mono. | ± | ∥ *b* | Y ∥ *b* | X∧*c*= —6°± | Z, Y brown X paler brown | Z>Y>X | Traces | ? |
| — | Mono.? | — | ∥ 001 | Z∧*c*= 3° to 20° | Y ∥ *b*± | Z green yellow Y indigo blue X olive green | Y>X>Z | Perf. ∥ 001 | ? |
| — | Tri. Ps. Hx. | | | ? | X ∥ *c*± | Colorless | | Dist. ∥ 001 | 1.72 |
| — | Tri. | + | ∥ *c* | X ⊥ 100 ± | Ext. on 100 = —30°± | Colorless | | Perf. ∥ 100<br>Perf. ∥ 010 | 1.72 |
| — | Tri. | — | ∥ 001 | Ext. on 010= —32° | Ext. on 100= +10° | Colorless | | Perf. ∥ 110<br>Perf. ∥ 1̄10<br>Dist. ∥ 001 | ? |

d. Birefringence rather strong >0.0185 <0.0275

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth. | + | ∥ *c* | Z ∥ *c* | Y ∥ *b* | Colorless | | Perf. ∥ 010 | 1.67 |
| + | Orth. | — | ∥ 001 | Z ∥ *c* | X ∥ *a* | Colorless | | Perf. ∥ 010<br>Perf. ∥ 001<br>Dist. ∥ 110 | 1.68 |
| + | Mono. | + | ∥ *c* | Z∧*c*= +25°± | Y ∥ *b* | Colorless | | Perf. ∥ 010 | 1.67 |
| + | Mono. | + | ∥ *c* | Z∧*c*= +41° | Y ∥ *b* | Colorless or green and blue | None or ? | Perf. ∥ 010 | 1.67 |
| + | Mono. | + | ∥ *c* | Z∧*c*= 30° to 44° | Y ∥ *b* | Colorless or Z pale green Y yellow green X pink | None or weak | Perf. ∥ 110<br>Parting ∥ 001 | 1.71 |
| + | Mono. | ± | ∥ *c* | Z∧*c*= +45° to +48° | Y ∥ *b* | Z greenish Y pale green X yellow green | Weak Z>Y>X | Perf. ∥ 110 | 1.7 |
| + | Mono. | ± | ∥ *c* | Z∧*c*= +38° to +54° | Y ∥ *b* | Colorless or Z greenish Y brownish, X greenish yellow | None or weak | Perf. ∥ 110 | 1.7<br>-1.7 |
| + | Mono. | ±? | ∥ *b*? | Y ∥ *b* | X ∥ *c*±? | Colorless or nearly so | | Dist. ∥ 001 | 1.7 |
| + | Mono. | — | ∥ 001 | Z ∥ *c*± | Y ∥ *b* | Colorless | | Traces | |
| + | Mono. | — | ∥ *c* | Z∧*c*= —18° to —21° | Y ∥ *b* | Z very pale yellow Y violet blue X green or blue | X>Y>Z | Perf. ∥ 110 | |

| $n_m$ | $n_p$ | $n_g - n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|
| 1.68<br>-1.71 | ? | 0.0123 | $2V$ large | ? | Hiortdahlite | $(Na_2,Ca)Fe(Si,Zr)_2O_6$ |
| 1.702 | 1.692<br>-1.7156 | 0.011<br>-0.013 | $2V=90°$<br>to 70° | $\rho<v$ | **Hypersthene** | $(Mg,Fe)SiO_3$ |
| 1.6805 | 1.6691 | 0.0127 | $2E=15°$<br>to 65° | $\rho>v$ | Kornerupine | $MgAl_2SiO_6$ |
| 1.686 | 1.678 | 0.011 | $2V=35°$<br>to 40° | $\rho<v$<br>strong | Dumortierite | $Al_8Si_3O_{18}$ |
| 1.7375 | 1.7312 | 0.0124 | $2V=68°$ | ? | Thalenite | $H_2Y_4Si_4O_{15}$ |
| 1.720<br>-1.753 | ? to<br>1.730 | 0.016<br>-0.054 | $2V=74°$<br>to 88° | $\rho>v$ | **Epidote** | $HCa_2(Al,Fe)_3Si_3O_{13}$ |
| 1.68<br>-1.70 | ? | 0.000<br>-0.032 | $2V=68°\pm$ | Strong | Allanite | Sil. of Al,Fe,Ca,Ce,H |
| 1.741 | ? | 0.007<br>-0.016 | $2E=65°$<br>to 120° | $\rho>v$<br>strong | Chloritoid | $H_2FeAl_2SiO_7$ |
| 1.7202 | 1.7148 | 0.0105 | $2V=83°$ | ? | Trimerite | $(Be,Mn,Ca)_2SiO_4$ |
| 1.720 | 1.712 | 0.016 | $2V=83°\pm$ | Incl.<br>weak | Cyanite | $Al_2SiO_5$ |
| 1.73 | ? | 0.010<br>-0.011 | $2V=76°$ | $\rho<v$<br>crossed | Rhodonite | $MnSiO_3$ |
| 1.658 | 1.656 | 0.020 | $2V=30°\pm$ | $\rho>v$ | Sillimanite | $Al_2SiO_5$ |
| 1.669 | 1.665 | 0.019<br>-0.021 | $2V=84°$ | ? | Lawsonite | $H_4CaAl_2Si_2O_{10}$ |
| 1.669 | 1.651 | 0.026 | $2V=54°$<br>to 60° | $\rho<v$ | Spodumene | $LiAl(SiO_3)_2$ |
| 1.655 | 1.652 | 0.019 | $2E=88°$ | $\rho>v$ | Euclase | $Be(AlOH)SiO_4$ |
| 1.691 | 1.690 | 0.021<br>-0.023 | $2E=13°$<br>to 67°+ | ? | Pigeonite | $(Mg,Fe,Ca)SiO_3$? |
| 1.7366 | 1.7320 | 0.0186 | $2V=60°$ | $\rho>v$ | **Hedenbergite** | $(Ca,Fe)SiO_3$ |
| 1.7039<br>-1.717 | 1.6975<br>-1.712 | 0.025<br>-0.021 | $2V=60°\pm$ | $\rho>v$<br>Incl. | **Augite** | Sil. of Ca,Mg,Fe,Al |
| 1.7291 | 1.7238 | 0.005<br>-0.020 | $2V=90°\pm$ | $\rho<v$ | Fouquéite | $H_2Ca_4Al_6Si_6O_{26}$ |
| 1.678 | ? | 0.021 | $2V=80°$ | $\rho>v$<br>horiz. | Homilite | $CaFe(BO)_2(SiO_4)_2$ |
| ? | ? | 0.025 | $2E=95°\pm$ | ? | Crocidolite | $NaFeSi_2O_6 \cdot FeSiO_3$ |

4. Refringence high $>1.66$ $<1.75$ (Cont.)

d. Birefringence rather strong $>0.0185$ $<0.0275$ (Cont.)

| SIGN | SYST. | ELONGATION | | | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
| | | Sign | Direc. | Ext. Ang. | | | | | |
| +? | Mono. | — | $\parallel b$ | $Z\wedge c=$ $13^\circ\pm$ | $X\parallel b$ | Colorless to pale yellow | $Z>Y>X$ | Perf. ‖ 001<br>Dist. ‖ 100 | ? |
| — | Mono. | + | ‖ 001 | $X\parallel c\pm$ | $Y\parallel b$ | Z, Y colorless X yellow brown | $Z=Y<X$ | Perf. ‖ 001 | 1.72 |
| — | Mono. | + | $\parallel c$ | $Z\wedge c=$ $+15^\circ$ to $+25^\circ$ | $Y\parallel b$ | Z green or yellow, Y green or brown, X yellow or brown Rarely colorless | $Z>Y>X$ | Perf. ‖ 110 | 1.68 |
| — | Mono. | ± | ‖ 100 | $X\wedge c=$ $-45^\circ\pm$ | $Y\parallel b$ | Colorless | | Dist. ‖ 010 | 1.72 |
| — | Mono. | ± | $\parallel b$ | $Y\parallel b$ | $X\wedge c=$ $-3^\circ\pm$ | Z yellow green Y blue to green yellow, X yellow or green | $Y>Z>X$ | Dist. ‖ 001 | ? to 1.76 |
| – | Mono. | -- | $\parallel c$ | $X\wedge c=$ $-12^\circ$ to $-15^\circ$ | $Y\parallel b$ | Z green yellow Y lavender blue X green blue | $X>Y>Z$ | Perf. ‖ 110 | 1.70 |

e. Birefringence strong $>0.0275$ $<0.0355$

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth.? | | | ? | ? | Z, Y yellow X red yellow | $X>Y=Z$ | | 1.70 |
| + | Orth. | ± | $\parallel c$ | $Y\parallel c$ | $Z\parallel a$ | Colorless | | Dist. ‖ 010 | ? |
| + | Mono. | | | $X\wedge a=$ $7^\circ$ to $12^\circ$ | $Z\parallel b$ | Colorless or Z, Y pale yellow X golden yellow | None or $X>Z>Y$ | Poor ‖ 001 | 1.69 |
| + | Mono. | + | $\parallel c$ | $Z\wedge c=$ $+33^\circ\pm$ | $Y\parallel b$ | Colorless | | Perf. ‖ 110 | ? |
| + | Mono. | ± | $\parallel c$ | $Z\wedge c=$ $+38^\circ$ to $+45^\circ$ | $Y\parallel b$ | Colorless or nearly so | | Perf. ‖ 110 | 1.70 -1.72 |
| + | Mono. | — | $\parallel c$ | $Z\wedge c=$ $+60^\circ+$ | $Y\parallel b$ | Z yellow or green, Y green, X dark green | $X>Y=Z$? | Perf. ‖ 110 | 1.70 |
| + | Tri. | —? | $\parallel c$ | Ext. on 100=44° | Ext. on 010=31° | Z dark brown or green, Y brown or yellow X green | $Z>X>Y$ | Perf. ‖ $1\bar{1}0$<br>Dist. ‖ 110 | ? |
| — | Mono. | + | $\parallel c$ | $Z\wedge c=$ $0^\circ$ to $+10^\circ$ | $Y\parallel b$ | Z, Y dark brown (or green) X yellow | $Z>Y>X$ | Perf. ‖ 110 | 1.70 -1.75 |
| — | Mono. | ± | $\parallel b$ | $Y\parallel b$ | $X\wedge c=$ $-3^\circ\pm$ | Z yellow green Y blue to green yellow, X yellow or green | $Y>Z>X$ | Dist. ‖ 001 | ? to 1.76 |
| — | Mono. | ± | $\parallel b$ | $Y\parallel b$ | $X\wedge c=$ $+6^\circ\pm$ | Z, Y brown X paler brown | $Z>Y>X$ | Traces | ? |
| — | Mono. | — | $\parallel c$ | $X\wedge c=$ $-20^\circ\pm$ | $Y\parallel b$ | Z yellow orange Y pale yellow X colorless | $Z>Y>X$ | Dist. ‖ 100 | ? |

f. Birefringence strong $>0.0355$ $<0.0445$

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth. | ± | $\parallel c$ | $Y\parallel c$ | $Z\parallel a$ | Colorless or nearly so | | Dist. ‖ 010 | 1.68 -1.70 |
| + | Orth. | — | $\parallel c$ | $X\parallel c$ | $Z\parallel b$ | Colorless to brown | $Y>Z>X$ | Dist. ‖ 120 | 1.78 |
| — | Mono. | + | $\parallel c$ | $Z\wedge c=$ $0^\circ$ to $+10^\circ$ | $Y\parallel b$ | Z, Y dark brown (or green) X yellow | $Z>Y>X$ | Perf. ‖ 110 | 1.70 -1.75 |

## iaxial Minerals (Cont.)

| $n_m$ | $n_p$ | $n_g-n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|
| 1.65 | ? | 0.026 | $2V=90^\circ\pm$ | ? | Rosenbuschite | Sil. of Ca,Ti,Zr,Na,F |
| 1.7287 | 1.7046 | 0.0252 | $2E=42^\circ$ | $\rho<v$ | Ganophyllite | Sil. of Al,Mn,H |
| 1.673 | 1.661 | 0.022 | $2V=84^\circ\pm$ | $\rho<v$<br>Incl. | **Hornblende** | Sil. of Al,Fe,Mg,Ca,Na |
| 1.716 | 1.700 | 0.026 | $2V=75^\circ\pm$ | $\rho<v$<br>dist. | Wöhlerite | Sil. of Zr,Nb,Ca,Na,F |
| 1.720<br>-1.753 | ? to<br>1.730 | 0.016<br>-0.054 | $2V=74^\circ$<br>to 88° | $\rho>v$ | **Epidote** | $HCa_2(Al,Fe)_3Si_3O_{13}$ |
| 1.707? | 1.687 | 0.021<br>-0.027 | $2V$ large | ? | Arfvedsonite | Sil. of Fe,Na,Al,Ca,Mg |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1.678 | 1.669 | 0.033 | $2E=120^\circ$ | $\rho>v$ | Titanolivine | $(Mg,Fe)_2(Si,Ti)O_4$ |
| 1.659 | ? | 0.035 ± | $2V=86^\circ\pm$ | $\rho<v$ | Forsterite | $Mg_2SiO_4$ |
| 1.670 | 1.658 | 0.032 | $2V=76^\circ$ | $\rho>v$<br>crossed | Clinohumite<br>(*cf.* Humite) | $[Mg(F,OH)]_2Mg_7(SiO_4)_4$ |
| 1.654 | ? | 0.029 | $2V=70^\circ$ | $\rho<v$ | Jadeite | $NaAl(SiO_3)_2$ |
| 1.680<br>-1.706 | 1.673<br>-1.699 | 0.030<br>-0.028 | $2V=59^\circ$<br>to 60° | $\rho>v$ | **Diopside** | $Ca(Mg,Fe)(SiO_3)_2$ |
| 1.687 | 1.680 | 0.029 | $2V=60^\circ\pm$ | $\rho>v$ | Ægyrinaugite | Sil. of Fe,Ca,Mg,Na,Al |
| 1.72 | ? | 0.032 | $2V=62^\circ\pm$ | Strong | Babingtonite | Sil. of Ca,Fe,Mn |
| 1.695<br>-1.725 | 1.677<br>-1.680 | 0.031<br>-0.072 | $2V=79^\circ\pm$ | $\rho<v$<br>Incl. | **Basaltic Hornblende** | Sil. of Fe,Al,Mg,Ca,Na |
| 1.720<br>-1.753 | ? to<br>1.730 | 0.016<br>-0.054 | $2V=74^\circ$<br>to 88° | $\rho>v$ | **Epidote** | $HCa_2(Al,Fe)_3Si_3O_{13}$ |
| 1.68<br>-1.70 | ? | 0.000<br>-0.032 | $2V=68^\circ\pm$ | Strong | Allanite | Sil. of Al,Fe,Ca,Ce,H |
| 1.750 | ? | 0.03 | $2V=80^\circ$ | Weak | Låvenite | Sil. of Na,Zr,Mn,Ca,Fe |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1.6703<br>-1.6899 | 1.6535<br>-1.6720 | 0.036<br>-0.037 | $2V=86^\circ$<br>to 90° | $\rho<v$ | **Chrysolite**<br>(**Olivine** proper) | $(Mg,Fe)_2SiO_4$ |
| ? | 1,7431 | 0.0445 | $2E=72^\circ$ | ? | Lorenzenite | $Na_2(Si,Ti,Zr)_3O_9$ |
| 1.695<br>-1.725 | 1.677<br>-1.680 | 0.031<br>-0.072 | $2V=79^\circ\pm$ | $\rho<v$<br>Incl. | **Basaltic Hornblende** | Sil. of Fe,Al,Mg.Ca,Na |

4. Refringence high >1.66 <1.75 (Cont.)

f. Birefringence strong >0.0355 <0.0445 (Cont.)

| SIGN | SYST. | ELONGATION |  |  | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Sign | Direc. | Ext. Ang. |  |  |  |  |  |
| — | Mono. | ± | $\parallel c$ | $Z \wedge c =$ $+3^\circ$ | $Z \parallel b$ | Colorless |  | Dist. ∥ 010 | 1.68 |
| — | Mono. | ± | $\parallel b$ | $Y \parallel b$ | $X \wedge c =$ $-3^\circ \pm$ | Z yellow green Y blue to green yellow, X yellow or green | Y>Z>X | Dist. ∥ 001 | ? t<br>1.76 |

g. Birefringence very strong >0.0445 <0.0565

| SIGN | SYST. | ELONGATION |  |  | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Sign | Direc. | Ext. Ang. |  |  |  |  |  |
| + | Orth. | ± | $\parallel c$ | $Y \parallel c$ | $Z \parallel a$ | Z lemon yellow Y, X golden yellow | X>Y>Z or Z>Y=X | Perf. ∥ 010 | 1.73 |
| + | Orth. | — | $\parallel c$ | $X \parallel c$ | $Z \parallel a$ | Colorless |  | Perf. ∥ 010 | 1.75 |
| + | Mono. | ± | $\parallel b$ | $Y \parallel b$ | $Z \wedge a =$ $32^\circ$ | Z red, Y violet X yellow | X>Y>Z | Dist. ∥ 010 |  |
| — | Orth. | ± | $\parallel c$ | $Y \parallel c$ | $X \parallel b$ | Colorless |  | ? | 1.73 |
| — | Mono. | + | $\parallel c$ | $Z \wedge c =$ $11^\circ$ to $+15^\circ$ | $Y \parallel b$ | Z yellow to brown Y, X colorless | Z>Y=X | Perf. ∥ 110 | ? |
| — | Mono. | + | $\parallel c$ | $Z \wedge c =$ $0^\circ$ to $+10^\circ$ | $Y \parallel b$ | Z,Y dark brown (or green) X yellow | Z>Y>X | Perf. ∥ 110 | 1.70<br>-1.75 |
| — | Mono. | ± | $\parallel b$ | $Y \parallel b$ | $X \wedge c =$ $-3^\circ \pm$ | Z yellow green Y blue to green yellow, X yellow to green | Y>Z>X | Dist. ∥ 001 | ? t<br>1.76 |
| — | Tri. |  |  | Ext. on 010=10° | Ext. on 100=26° | Colorless |  | Perf. ∥ 001 | >1.7 |

h. Birefringence extreme >0.0565

| SIGN | SYST. | ELONGATION |  |  | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | $n_g$ |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Sign | Direc. | Ext. Ang. |  |  |  |  |  |
| + | Mono. | + | $\parallel c$ | $Z \wedge c =$ $-12^\circ$ | $Y \parallel b$ | Green in mass | ? | Perf. ∥ 001 | 1.714 |
| — | Orth. | — | $\parallel c$ | $X \parallel c$ | $Z \parallel b$ | Colorless |  | Dist. ∥ 010 | 1.68 |
| — | Orth. | — | $\parallel c$ | $X \parallel c$ | $Z \parallel b$ | Colorless |  | Poor ∥ 110 | 1.670 |
| — | Orth. | — | $\parallel c$ | $X \parallel c$ | $Z \parallel a$ | Colorless |  | Dist. ∥ 110 | 1.66 |
| — | Orth. | — | $\parallel c$ | $X \parallel c$ | $Z \parallel a$ | Colorless |  | Dist. ∥ 110 | 1.67 |
| — | Mono. | + | $\parallel c$ | $Z \wedge c =$ $11^\circ$ to $+15^\circ$ | $Y \parallel b$ | Z yellow to brown Y, X colorless | Z>Y=X | Perf. ∥ 110 | ? |
| — | Mono. | + | $\parallel c$ | $Z \wedge c =$ $0^\circ$ to $10^\circ$ | $Y \parallel b$ | Z,Y dark brown (or green) X yellow | Z>Y>X | Perf. ∥ 010 | 1.70<br>-1.75 |
| — | Mono. | + | $\parallel c$ | $Z \wedge c =$ $-31^\circ$ | $X \parallel b$ | Red, green, blue | Pleoch. | Perf. ∥ 010 | 1.69 |
| — | Mono. | ± | $\parallel c$ | $X \wedge c =$ $+65^\circ$ | $Z \parallel b$ | Colorless |  | Perf. ∥ 110 | 1.68 |

## xial Minerals (Cont.)

| | $n_m$ | $n_p$ | $n_g - n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|---|
| 8 | 1.6609 | 1.6445 | 0.043 | $2V=77°$ | $\rho > v$ strong | Leucosphenite | Sil. of Ba,Na,Ti |
| | 1.720 -1.753 | ? to 1.730 | 0.016 -0.054 | $2V=74°$ to 88° | $\rho > v$ | **Epidote** | $HCa_2(Al,Fe)_3Si_3O_{13}$ |

| | $n_m$ | $n_p$ | $n_g - n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|---|
| | 1.703 | 1.678 | 0.055 | $2V=70°$ to 80° | ? | Astrophyllite | Sil. of Fe,Mn,Ti,Zr,Na,H |
| | 1.722 | 1.702 | 0.048 | $2V=84°$ | $\rho < v$ | Diaspore | AlO(OH) |
| | ike epidote | | 0.05± | $2V=79°\pm$ | ? | Piedmontite | $HCa_2(Al,Mn)_3Si_3O_{13}$ |
| | 1.722 | 1.686 | 0.049 | $2V=61°$ | $\rho > v$ dist. | Glaucochroite | $MnCaSiO_4$ |
| | 1.73 | ? | 0.056 | $2V=50°\pm$ | $\rho > v$ | Grünerite | $FeSiO_3$ |
| | 1.695 -1.725 | 1.677 -1.680 | 0.031 -0.072 | $2V=79°$ | $\rho < v$ Incl. | **Basaltic Hornblende** | Sil. of Fe,Al,Mg,Ca,Na |
| | 1.720 -1.753 | ? to 1.730 | 0.016 -0.054 | $2V=74°$ to 88° | $\rho > v$ | **Epidote** | $HCa_2(Al,Fe)_3Si_3O_{13}$ |
| | ? | <1.665 | >0.041 | $2E=80°$ to 90° | ? | Tarbuttite | $Zn_2(OH)PO_4$ |

| | $n_m$ | $n_p$ | $n_g - n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|---|
| | 1.6555 | 1.6491 | 0.0652 | $2V=37°$ | $\rho < v$ strong | Natrochalcite | $Na_2Cu_4(OH)_2(SO_4)_3+2H_2O$ |
| | 1.682 | 1.530 | 0.156 | $2E=31°$ | $\rho < v$ | **Aragonite** | $CaCO_3$ |
| | 1.670± | 1.525 | 0.145 | $2E=10°$ | Weak | Bromlite | $(Ca,Ba)CO_3$ |
| | 1.664 | 1.518 | 0.147 | $2E=10°$ | $\rho < v$ | **Strontianite** | $SrCO_3$ |
| | 1.676 | 1.529 | 0.148 | $2E=26°$ | $\rho > v$ | **Witherite** | $BaCO_3$ |
| | 1.73 | ? | 0.056 | $2V=50°\pm$ | $\rho > v$ | Grünerite | $FeSiO_3$ |
| | 1.695 -1.725 | 1.677 -1.680 | 0.031 -0.072 | $2V=79°\pm$ | $\rho < v$ Incl. | **Basaltic Hornblende** | Sil. of Fe,Al,Mg,Ca,Na |
| | 1.6614 | 1.6263 | 0.0723 | $2H=105°$ | $\rho > v$ weak | Erythrite | $Co_3(AsO_4)_2+8H_2O$ |
| | 1.684 | 1.525 | 0.161 | $2E=24°$ | $\rho > v$ weak | Barytocalcite | $BaCa(CO_3)_2$ |

### 5. Refringence very high >1.75

#### a. Birefringence unknown

| SIGN | SYST. | ELONGATION | | | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | |
|---|---|---|---|---|---|---|---|---|---|
| | | Sign | Direc. | Ext. Ang. | | | | | |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *b* | Z colorless to pink<br>X bluish green | ? | Poor ∥ 120 | |
| + | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *b* | Z green to opaque, Y brown yellow, X brown to black | Z>X>Y | Poor ∥ 001<br>Poor ∥ 010 | |
| + | Orth. | ± | ∥ *c* | Y ∥ *c* | Z ∥ *a* | Green, brown, white in mass | Weak pleoch. | Traces | |
| + | Mono. | ? | ∥ *c* | Ext. on 010= 8° to 11° | ? | Hyacinth red | ? | Perf. ∥ 010 | |
| + | Mono. | + | ∥ *c* | $X \wedge c = +6^\circ \pm$ | Y ∥ *b* | Colorless | | Perf. ∥ 010 | |
| — | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *b* | Colorless | | Perf. ∥ 010 | |
| — | Orth. | + | ∥ 001 | X ∥ *c* | Z ∥ *b* | Cherry red | ? | Poor ∥ 001 | |
| — | Orth. | ± | ∥ *c* | Y ∥ *c* | X ∥ *a* | Colorless | | Perf. ∥ 010 | |
| — | Orth. | ± | ∥ *a* | Y ∥ *a* | X ∥ *b* | Green in mass | Pleoch. | Perf. ∥ 001 | |
| — | Mono. | | | X ∥ *c*± | Y ∥ *b* | Lemon yellow | ? | Dist. ∥ 001 | |

#### a. Birefringence very weak <0.0035

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | |
|---|---|---|---|---|---|---|---|---|---|
| + | Mono. | + | ∥ *c* | $Z \wedge c = -4^\circ$ to $-13^\circ$ | Y ∥ *b* | Green or brown | None | None | |
| ± | Ps. Is. | | | ? | ? | Gray, brown, red, green | ? | Poor ∥ 100 | |

#### b. Birefringence weak >0.0035 <0.0095

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth. | ± | ∥ 100 | Y ∥ *a* | Z ∥ *c* | Colorless | | Poor ∥ 011<br>Poor ∥ 010 | 1. |
| ± | Ps. Is. | | | ? | ? | Gray, brown, red, green | ? | Poor ∥ 100 | |
| — | Hex.? | — | ∥ *c* | 0° | X ∥ *c* | Green, yellow, brown, gray in mass | ? | Traces | 2. |

#### c. Birefringence moderate >0.0095 <0.0185

| SIGN | SYST. | Sign | Direc. | Ext. Ang. | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | |
|---|---|---|---|---|---|---|---|---|---|
| + | Mono. | + | ∥ *c* | $Z \wedge c = -4^\circ$ to $-13^\circ$ | Y ∥ *b* | Green or brown | None | None | |
| + | Mono. | + | ∥ 010 | $Z \wedge c = -43^\circ$ | X ∥ *b* | Colorless to brown | | ? | |
| — | Hex.? | — | ∥ *c* | 0° | X ∥ *c* | Yellow, brown, or white in mass | ? | Traces | 2. |

## iaxial Minerals (Cont.)

|  | $n_m$ | $n_p$ | $n_g-n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|---|
|  | 1.84 | ? | ? | 2E=115° | $\rho>v$ strong | Scorodite | $FeAsO_4+2H_2O$ |
|  | 1.89 | ? | ? | 2E=60°± | ? | Ilvaite | $CaFe_2(FeOH)(SiO_4)_2$ |
|  | 1.83 | ? | ? | 2H=106° | $\rho>v$ strong | Olivenite | $Cu(CuOH)AsO_4$ |
|  | ? | ? | ? | ? | ? | Pyrostilpnite | $Ag_3SbS_3$ |
|  | ? | ? | ? | 2H=65° | $\rho<v$ strong | Claudétite | $As_2O_3$ |
|  | Very high | ? | ? | 2H=140° | ? | Tellurite | $TeO_2$ |
|  | ? | ? | ? | 2E=66° to 88° | ? | Polybasite | $Ag_9SbS_6$ |
|  | 2.34 | ? | ? | 2V small | $\rho>v$ very strong | Valentinite | $Sb_2O_3$ |
|  | 1.846 | ? | ? | 2V=83° | $\rho<v$ weak | Caledonite | $(Pb,Cu)_2(OH)_2SO_4$ |
|  | ? | ? | ? | 2E=125° | $\rho<v$ | Xanthoconite | $Ag_3AsS_3$ |

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
|  | >1.78 | ? | 0.000 to strong | 2V=85° | $\rho<v$ strong | Gadolinite | $Be_2Fe(YO)_2(SiO_4)_2$ |
|  | 2.38 | ? | 0.000 -0.007 | 2V=90°± | $\rho>v$ | Perovskite | $CaTiO_3$ |

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| 56 | 1.748 | 1.747 | 0.009 | 2E=85° | $\rho>v$ | Chrysoberyl | $BeAl_2O_4$ |
|  | 2.38 | ? | 0.000 -0.007 | 2V=90°± | $\rho>v$ | Perovskite | $CaTiO_3$ |
| 04 | ? | 2.0420 | 0.0084 | Uniaxial or 2V small | ? | Pyromorphite | $Pb_4(PbCl)(PO_4)_3$ |

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
|  | >1.78 | ? | 0.000 to strong | 2V=85° | $\rho<v$ strong | Gadolinite | $Be_2Fe(YO)_2(SiO_4)_2$ |
|  | ? | ? | 0.01± | 2V=80°± | ? | Hellandite | $Ca[(Al,Y,Er,Fe)OH]_3Si_2O_8$ |
| 49 | ? | 2.1180 | 0.0169 | 2E=0° to 64° | ? | Mimetite | $Pb_4(PbCl)(AsO_4)_3$ |

### 5. Refringence very high >1.75 (Cont.)

#### d. Birefringence rather strong >0.0185 <0.0275

| SIGN | SYST. | ELONGATION |  |  | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE | *n* |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Sign | Direc. | Ext. Ang. |  |  |  |  |  |
| + | Orth. |  |  | Z ∥ *a* | X ∥ *c* | Colorless |  | Dist. ∥ 001<br>Dist. ∥ 110 | 1.8 |
| + | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *b* | Z pale yellow<br>Y, X golden yellow | Z<Y=X | Perf. ∥ 010<br>Dist. ∥ 110 | ? |
| + | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *a* | Z brown<br>Y red brown<br>X yellow brown | Z>Y or Z=Y>X | Dist. ∥ 100 | ? |
| — | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *b* | Z grass green<br>Y yellow green<br>X pale green | ? | Perf. ∥ 010 | ? |

#### e. Birefringence strong >0.0275 <0.0355

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| + | Mono. | + | ∥ *c* | Z∧*c*= −4° to −13° | Y ∥ *b* | Green or brown | None | None | ? |
| — | Orth. | ± | ∥ *c* | Y ∥ *c* | X ∥ *b* | Colorless or Z, X green yellow, Y orange yellow | Y>X>Z or Y>X=Z | Dist. ∥ 010 | 1.8 |
| — | Mono. | ± | ∥ *c* | X∧*c*= —49° | Y ∥ *b* | Hyacinth red to olive green | Pleoch. | Dist. ∥ 101 | ? |
| — | Mono. | — | ∥ *c* | X∧*c*= +11° | Y ∥ *b* | Z, Y vermilion<br>X orange red | Z=Y>X | Perf. ∥ 010<br>Dist. ∥ 001<br>Dist. ∥ 100 | ? |
| — | Mono. | — | ∥ *c* | X∧*c*= —20°± | Y ∥ *b* | Z yellow to red<br>Y, X colorless to yellow | Z>Y>X | Dist. ∥ 100 | ? |

#### f. Birefringence strong >0.0355 <0.0445

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *b* | Colorless to brown | Y>Z>X | Dist. ∥ 120 | 1.7 |
| + | Orth. | — | ∥ 100 | Z ∥ *a* | X ∥ *b* | Brown to black | Y>Z=X | Dist. ∥ 010 | ? |
| ± | Orth. | — | ∥ *c* | X ∥ *c* | Y ∥ *b* | Red, brown or black in mass | ? | None | ? |
| — | Orth. | ± | ∥ *c* | Y ∥ *c* | X ∥ *b* | Colorless to very pale green |  | Dist. ∥ 010 | ? |

#### g. Birefringence very strong >0.0445 <0.0565

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| + | Orth. | — | ∥ *c* | X ∥ *c* | Z ∥ *b* | Colorless to brown | Y>Z>X | Dist. ∥ 120 | 1.7 |
| + | Mono.?<br>Ps. Tet.? | + | ∥ *c* | 0° | Z ∥ *c* | Colorless to pale brown or gray |  | Poor ∥ 110 | 1.9 |
| + | Mono. | ± | ∥ 100 | Z∧*c*= +4°± | X ∥ *b* | Colorless to yellowish | Y>Z=X | Dist. ∥ 100 | 1.8 |
| — | Orth. | + | ∥ *c* | Z ∥ *c* | X ∥ *b* | Z orange yellow<br>Y brownish yellow, X yellow | Y>Z>X | ∥ 100 | ? |
| — | Orth. | ± | ∥ *c* | Y ∥ *c* | X ∥ *b* | Z, X green yellow<br>Y orange yellow | Y>Z>X or Y>Z=X | Dist. ∥ 010 | 1.8 |

## axial Minerals (Cont.)

| | $n_m$ | $n_p$ | $n_g-n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|---|
| 7 | 1.883 | 1.877 | 0.020 | $2V=70^\circ\pm$ | $\rho<v$ | Anglesite | $PbSO_4$ |
| | 1.79± | ? | 0.020 | $2E=73^\circ\pm$ | $\rho>v$ strong | Ardennite | Sil. of V,Al,Mn,H |
| | Very high | ? | 0.022 | $2E=62^\circ\pm$ | ? | Warwickite | $(Mg,Fe)_4Be_2TiO_9$ |
| | ? | ? | 0.022 | $2H=93^\circ$ | $\rho<v$ strong | Atacamite | $Cu_2(OH)_3Cl$ |
| | >1.78 | ? | 0.000 to strong | $2V=85^\circ$ | $\rho<v$ strong | Gadolinite | $Be_2Fe(YO)_2(SiO_4)_2$ |
| 31 | 1.7915 | 1.7684 | 0.035 | $2V=70^\circ\pm$ | $\rho>v$ | Hortonolite (Olivine) | $(Fe,Mg)_2SiO_4$ |
| | 1.786 | ? | Strong | $2H=9^\circ$ | $\rho>v$ very strong | Allactite | $Mn_3(AsO_4)_2\cdot 4Mn(OH)_2$ |
| | ? | ? | Strong | $2H=93^\circ$ | $\rho>v$ Incl. strong | **Realgar** | $AsS$ |
| | 1.750 | ? | 0.03 | $2V=80^\circ$ | Weak | Låvenite | Sil. of Na,Zr,Mn,Ca,Fe |
| 76 | ? | 1.7431 | 0.0445 | $2E=72^\circ$ | ? | Lorenzenite | $Na_2(Si,Ti,Zr)_3O_9$ |
| | ? | ? | Strong | $2H=85^\circ$ | $\rho>v$ dist. | Pseudobrookite | $Fe_4(TiO_4)_3$? |
| | 1.83 | ? | Strong | $2H=97^\circ$ | $\rho<v$ strong | Descloizite | $(Pb,Zn)(PbOH)VO_4$ |
| | Very high | ? | Strong | $2V=60^\circ\pm$ | $\rho>v$ | Hortonolite (Olivine) | $(Fe,Mg)_2SiO_4$ |
| 76 | ? | 1.7431 | 0.0445 | $2E=72^\circ$ | ? | Lorenzenite | $Na_2(Si,Ti,Zr)_3O_9$ |
| 20 | 1.9277 | 1.9272 | 0.0548 | $2V=10^\circ$ | ? | Beccarite (Zircon) | $(Zr,Si)O_2$ |
| 11 | 1.7965 | 1.7957 | 0.0454 | $2E=77^\circ\pm$ | $\rho<v$ | **Monazite** | $(Ce,La,Di)PO_4$ |
| | 2.5 | ? | 0.048 | $2V$ large | $\rho>v$ strong | **Limonite** | $Fe_4(OH)_6O_3$ |
| 36 | 1.8641 | 1.8236 | 0.050 | $2V=50^\circ$ | $\rho>v$ | **Fayalite** | $Fe_2SiO_4$ |

### 5. Refringence very high >1.75 (Cont.)

### g. Birefringence very strong >0.0445 <0.0565 (Cont.)

| SIGN | SYST. | ELONGATION | | | OPT. ORIENT. | COLOR | ABSORP. | CLEAVAGE |
|---|---|---|---|---|---|---|---|---|
| | | Sign | Direc. | Ext. Ang. | | | | |
| — | Orth. | ± | $\parallel c$ | $Y \parallel c$ | $X \parallel b$ | Z greenish blue<br>Y, X reddish | Y>Z>X | Dist. ‖ 010 |
| — | Mono. | + | $\parallel b$ | $Z \parallel b$ | $X \wedge a = -24°$ | Blue in mass | ? | Perf. ‖ 100<br>Poor ‖ 001 |
| — | Mono. | — | $\parallel c$ | $X \wedge c = +5° \pm$ | $Y \parallel b$ | Z yellow to green Y green X green to brown | X>Y>Z | Perf. ‖ 110 |

### h. Birefringence extreme >0.0565

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| + | Orth. | | | $Z \parallel c$ | $Y \parallel b$ | Yellow in mass | | Poor ‖ 001<br>Poor ‖ 110 |
| + | Orth. | ± | $\parallel c$ | $Y \parallel c$ Na light | $Z \parallel a$ | Yellow and brown | Z>Y>X or Z<Y>X | Traces |
| + | Orth. | ± | ‖ 100 | $Y \parallel a$ | $Z \parallel c$ | Brown in mass | ? | Perf. ‖ 100 |
| + | Mono. | + | $\parallel c$ | $Z \wedge c = -5° \pm$ | $Y \parallel b$ | Red in mass | ? | Dist. ‖ 110 |
| + | Mono. | + | $\parallel c$ | $Z \wedge c = -12°$ | $Y \parallel b$ | Pale blue | ? | Perf. ‖ 021<br>Poor ‖ 100 |
| + | Mono. | — | ‖ 001 | $Z \wedge c = +51° \pm$ | $Y \parallel b$ | Colorless or nearly so | ? | Dist. ‖ 110 |
| — | Orth. | + | $\parallel c$ | $Z \parallel c$ | $X \parallel a$ | Colorless | | Dist. ‖ 100 |
| — | Orth. | + | $\parallel c$ | $Z \parallel c$ | $X \parallel b$ | Bright red | Weak | Dist. ‖ 100 |
| — | Orth. | ± | $\parallel c$ | $Y \parallel c$ Na light | $X \parallel b$ | Z orange yellow<br>Y brown yellow<br>X brown | Y>X>Z | Perf. ‖ 010 |
| — | Orth. | — | $\parallel c$ | $X \parallel c$ | $Z \parallel a$ | Colorless | | Dist. ‖ 110<br>Dist. ‖ 021 |
| — | Orth. | — | $\parallel c$ | $X \parallel c$ | $Z \parallel b$ | Red to black | ? | Perf. ‖ 010 |
| — | Mono. | + | ‖ 001 | $X \parallel c \pm$ | $Y \parallel b$ | Colorless | | Perf. ‖ 001 |
| — | Mono. | — | ‖ 100 | $X \wedge c = +12° \pm$ | $Y \parallel b$ | Colorless to brown | Weak | Dist. ‖ 001<br>Poor ‖ 010<br>Parting ‖ 110 |
| — | Mono. | — | $\parallel c$ | $X \wedge c = +23°$ | $Y \parallel b$ | Green in mass | ? | Perf. ‖ 001<br>Poor ‖ 010 |
| — | Mono. | — | ‖ 001 | $X \wedge c = +84°$ | $Y \parallel b$ | Vermilion | None | Perf. ‖ 100 |

## iaxial Minerals (Cont.)

| g | $n_m$ | $n_p$ | $n_g - n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|---|
| ? | 1.80 | ? | Strong | $2E=160°$ | $\rho>v$ | Tephroite | $Mn_2SiO_4$ |
| 593 | 1.8380 | 1.8092 | 0.050 | $2V=80°$ | $\rho<v$ dist. | Linarite | Sul. of Pb,Cu,H |
| 126 | 1.7990 | 1.7630 | 0.0486 | $2V=62°$ | $\rho>v$ | Acmite | $NaFe(SiO_3)_2$ |

| g | $n_m$ | $n_p$ | $n_g - n_p$ | OPT. ANG. | DISP. | NAME | COMPOSITION |
|---|---|---|---|---|---|---|---|
| 405 | 2.0383 | 1.9505 | 0.290 | $2V=69°$ | $\rho<v$ | **Sulphur** | S |
| 414 | 2.5856 | 2.5832 | 0.1582 | $2E=0°$ to 55° | $\rho>v$ extreme | Brookite | $TiO_2$ |
| 568<br>588 | 2.4039<br>-2.4190 | 2.3742<br>-2.3977 | 0.0826<br>-0.0611 | $2V=73°$ to 75° | $\rho<v$ strong | Stibiotantalite | $(SbO)_2(Ta,Nb)_2O_6$ |
|  | 2.42 | ? | Strong | $2V$ large | Incl. strong | Crocoite | $PbCrO_4$ |
| ? | ? | ? | 0.200 | $2E=151°$ | $\rho>v$ Horiz. dist. | **Azurite** | $Cu_3(OH)_2(CO_3)_2$ |
| 093 | 1.8940 | 1.8879 | 0.1214 | $2V=27°\pm$ | $\rho>v$ strong | **Titanite** | $CaTiSiO_5$ |
| 580 | 2.1161 | 2.0767 | 0.0813 | $2V=82°$ | ? | Laurionite | $Pb(OH)Cl$ |
| 88 | 3.176 | 3.078 | 0.110 | $2V$ small | ? | Hutchinsonite | $Pb(Tl,Ag)_2As_4S_8$ |
| ? | 2.5± | ? | 0.134 | $2E=0°$ to 68° | $\rho<v$ extreme | **Goethite** | $FeO(OH)$ |
| 078 | 2.076 | 1.804 | 0.274 | $2E=17°$ | $\rho>v$ dist. | **Cerussite** | $PbCO_3$ |
| 03 | 4.046 | 3.194 | 1.109 | $2V=26°$ | Very strong | **Stibnite** | $Sb_2S_3$ |
| ? | ? | ? | 0.070 | $2E=23°\pm$ | $\rho<v$ strong | Leadhillite | $(PbOH)_2Pb_3(CO_3)_2SO_4$ |
| ? | Very high | ? | Very strong | $2E=72°\pm$ | ? | Baddeleyite | $ZrO_2$ |
| ? | 1.88 | ? | 0.200 | $2E=89°$ | ? | **Malachite** | $Cu_2(OH)_2CO_3$ |
| ? | 3.27 | ? | Very strong | $2V=65°\pm$ | ? | Smithite | $AgAsS_2$ |

# APPENDIX I.

## THE OPTICAL STUDY OF OPAQUE MINERALS.

While our knowledge of the microscopic characters of transparent minerals has increased with remarkable rapidity during the last fifty years, that of the optic characters of opaque minerals has remained at a standstill in a very unsatisfactory condition. Mineralogists are to be congratulated that there is good reason to believe that a new era is at hand when we shall be able to study the opaque minerals microscopically with results not greatly inferior to those obtained at present with transparent minerals.

During the last two years several articles have appeared by Campbell[1] and Knight which have been especially notable as representing the successful application of the methods of metallography to the study of opaque minerals. By very careful polishing of surfaces on opaque minerals, and powerful vertical illumination, these investigators have made important discoveries concerning the microstructure of the minerals studied. They have examined chiefly samples of copper, nickel, and iron ores by the methods of metallography and have obtained results which have important bearings on the origin of certain ore deposits. But these methods involve simply a study of structures, and not a study of the internal characters of the respective minerals, such as is revealed by the polarizing microscope as applied to transparent minerals. The only knowledge of internal characters obtained by the metallographist is that derived from the study of etching figures, and these are not easily obtained, especially on surfaces only of microscopic size.

The development of a method of microscopic investigation which permits determination of the internal optical characters of opaque minerals is manifestly of the utmost importance; its accomplishment is of such recent date that the possibilities of the new method can not yet be fully stated, but it is clear that it will result in a marked increase in our knowledge of opaque minerals, and that we shall no longer consider that the minerals that make up the bulk of all our ore deposits are outside the field of optical microscopic study.

The new method of study is due to the ability of Johan Königsberger[2], who has devised apparatus by means of which he is able to distinguish at a glance between isotropic and anisotropic opaque minerals, to determine the pleochroic formula in reflected light, to determine quantitatively the relative reflecting power for rays vibrating in different directions, and to determine the exact position of the axes of ether vibration. It is clear that this last determination will give angles corresponding exactly to extinction angles, and will thus indicate the relation between the internal symmetry and the apparent external symmetry. It will disclose twinning, whether this complexity is evident from the external form or not.

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[1] *Econ. Geol.* I. p. 751. I. p. 767. II. p. 350.

[2] *Centralb. für Mineralogie*, etc. 1908, pp. 565-573, 597-605.

The chief difficulties encountered in undertaking studies by the new method are due to the delicacy of the apparatus employed and the necessity for obtaining a very high polish on the material examined. The preparation of this polished surface is said to require about three hours' time in the hands of an experienced workman. While these difficulties will undoubtedly prevent a wide usage of the new method, they are apparently little if any greater than the difficulties encountered at the birth of modern petrography.

The following condensed translation of Königsberger's articles was prepared by Mr. Edward Steidtmann:

## AN APPARATUS FOR THE RECOGNITION AND MEASUREMENT OF OPTICAL CHARACTERISTICS OF OPAQUE SUBSTANCES.

The apparatus enables one to detect the presence of anisotropic substances in a polished surface of an opaque fragment, and to determine their optical orientation, as well as to measure the difference between the reflecting capacity (the ratio $\frac{R_1}{R_2}$) of any two mutually perpendicular directions.

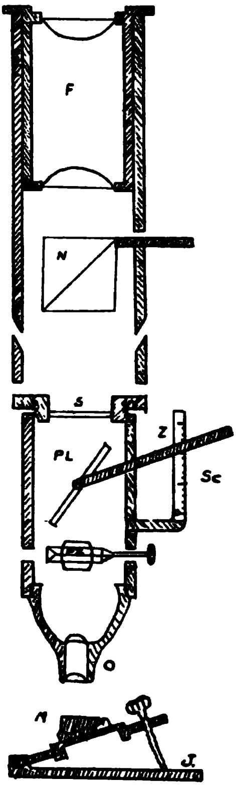

**Fig. 1. Königsberger's apparatus.**

This mechanism can be used in the optical study of minerals which are opaque even in thin sections, in the investigation of ore specimens and rocks containing ores, and in the physico-chemical study of metals, alloys, and meteorites.

The apparatus consists essentially of the following parts: (fig 1) *Ps* is a totally reflecting, precisely rectangular prism which is slightly eccentric in its position. *S* is a very carefully ground and adjusted Savart plate, consisting of a calcite double plate (cut at less than 45°), crossed, and 0.6 mm. in total thickness.

*N* is the central nicol, which must not have too small an aperture; *F*, a telescope with approximately seven fold magnification and a focus at infinity. *O* is the objective of the microscope with a focal distance of 5.3 cm. (Zeiss achromatic *AA* or *DD*.) *AA* which produces a magnification of 100 diameters with the telescope is the best suited for this purpose. In order to use *DD* and in general for very accurate measurements, it is advisable to use in place of the ordinary totally reflecting eccentric prism, a centric prism with a cylindrical prism similar to Nachet's to set on its central surface. The images would be then clearer, brighter and free from polarization, even under high magnification.

*M* is the prepared substance. *J* is the adjusting device. *Pl* is a glass plate whose inclination with the microscopic axis can be changed to any desired angle. (Indicator *Z* and scale *Sc*). Since the reflecting power of glass for the directions of vibration parallel and perpendicular to the plane of incidence varies with the angle, and since it can be calculated from the index of refraction and the angle of incidence to within 0.2%, a table which is applicable to yellow light is added to the scale. This table gives directly the amount of polarization, and from this is obtained the relation of the reflection in the two directions on the prepared substance whose difference has been compensated by the glass plate.

The telescope of the apparatus is focused on infinity and the plate *Pl* is placed in a position normal to the axis of the microscope. Then a source of light, (Welsbach intense sodium light, or mercury lamp) and a lens are placed on the table at exactly the same elevation as the aperture of the totally reflecting prism, and a somewhat diffused image of the source of light is thrown upon the aperture. Following this any isotropic metallic mirror is placed under the microscope. At this juncture, the Savart bands must not be visible, but they should appear in the middle of the field of view if the glass plate is now rotated through a large angle. Two of the Savart bands are nearly black and achromatic. If the plate *Pl* is turned back to the zero position, the bands again disappear. When the glass plate is in a horizontal position and the metallic mirror is replaced by a cleavage plate of stibnite, the bands appear brightest in four positions of a complete rotation, and disappear entirely in four intermediate rectangular positions. This indicates that the reflecting capacity of the substance is not uniform in all directions, i. e., the substance is anisotropic. If the substance is composed of both anisotropic and isotropic portions, then the bands appear only in the former.

The plates should be so placed on the stage that their reflecting surfaces are perpendicular to the axis of the microscope and to that of the rotating stage. This position is recognized by the fact that the illumination is unchanged when the stage is rotated with the plate. In order to facilitate this adjustment, I have had the firm of Voigt & Hochgesang construct a small adjusting device, consisting of a screw and small rotating table. This device is to be preferred to the conventional adjustment by means of three screws, because of its more stable position and its simple manipulation.

The focusing of the microscope is accomplished by a sharp focus on the reflecting surface to be investigated.

If the reflecting surface is homogeneous, the Savart bands are all perceived simultaneously. This is the case in cleavage plates of stibnite and natural crystals of pyrite.

Frequently, however, in ore samples, and alloys, the surface presents, when moderately polished, a maze of striæ, fracture, and crystal boundaries, and this makes the recognition of the Savart bands difficult, when these are not clearly defined. One can overcome this difficulty in either one of two ways; namely, by using the most powerful objective, when a greater portion of the field will present a homogeneous reflecting surface, or by either raising or lowering the microscope tube so that the focus is ill-defined and fractures and striæ partially disappear. Occasionally both methods can be employed simultaneously. Sometimes, it is necessary to obtain more perfect polish.

The manipulation of the apparatus is of course not as simple as the mere determination of luster and streak of a mineral. Its introduction might therefore be regarded as a retrogressive step in comparison with the macroscopic diagnosis. If one considers, however, that the introduction of microscopic study of transparent substances brought about a tremendous complication of methods, and nevertheless proved to be of extreme usefulness, it may be hoped that this method may prove to be of similar, though perhaps more limited, service in the study of opaque minerals.

The recognition of anisotropic opaque substances by this method proves to be very simple. A glance in the microscope shows that the spherical botryoidal minerals from Erzbergwerk am Schauinsland (Freiburg i. B.), which are commonly described as pyrite are a mixture of pyrite and marcasite. The glauconite of Hakansboda cut parallel to 001 proves to be intergrown with a differently oriented, weakly anisotropic substance, namely chalcopyrite.

This method also supplements the study of twinning in a very desirable manner, since the principal optic directions of the various crystals can be determined easily.

Several ore samples reveal their isotropic and anisotropic constituents. In mineral diagnosis, the knowledge of the isotropic or anisotropic character of minerals is very important. The methods also enable the observer to determine the relation of the optic directions to the crystal outline, and from this the relation between optic and crystallographic symmetry can be inferred.

The apparatus may prove especially useful in the study of symmetry relations of chemically homogeneous minerals. The relations for example of the crystallographic and optic symmetry of a plane can be determined. For this and the following measurements, a contrasting device is attached in front of the totally reflecting prism. This contrasting device consists of a lens and two slightly colored, smoky quartz plates, which are at right angles to each other. As a result of its use the Savart bands are feebly visible in the ocular, and they are shifted half the width of a band in the two halves of the field of view, but their sharpness and contrast are the same in the two halves.

If the plate on the stage is very weakly anisotropic, then the bands become more distinct in one-half of the field and tend to disappear in the opposite half. This contrast can easily be distinguished, as a difference of 0.3% in reflecting capacity can be determined with certainty.

As will be explained later the relation of optic symmetry lines to crystallographic symmetry lines can readily be determined in the same manner; while heretofore very painstaking observation, and very trying calculations were necessary to achieve the same result, as for instance, the careful study of E. C. Müller † on stibnite and of Försterling ‡ on hematite.

The sensitiveness of the device as well as the entire apparatus can be tested best on transparent anisotropic material. It is theoretically best to use only one surface. In this case the rear surface is covered with black shellac. If the plate has parallel sides both surfaces could be employed.

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† *N. Jahrb. f. Min.* Beil. Bd. XVII. p. 187. 1903.
‡ *N. Jahrb. f. Min.* XXV. p. 350. 1908.

From Fresnel's intensity formulas one can deduce that in weak double refraction for reflection on one surface $\frac{I}{I'} = \frac{4d}{(n'-1)\ (n'+1)}$ in which $n'$ is the greater index of refraction, $I'$ is the complementary reflected intensity and $d$ is the magnitude of double refraction. For a cleavage plate of gypsum of any thickness, the intensity ratio for sodium light is exactly 1% for the two surfaces if they are in the correct position; for mica, it is 1.5%. It follows that these values can be easily recognized. For the calibration of the glass plate for measuring the ratio of intensity the following serve: Quartz parallel to the axis: 1 or 2 surfaces, $\frac{I}{I'} = 0.958$; calcite parallel to the axis: 1 surface $\frac{I'}{I} = 0.623$; 2 surfaces $\frac{I}{I'} = 0.637$; mica: 1 or 2 surfaces $\frac{I}{I'} = 0.985$. These constants can readily be calculated for any color and from them the glass plate can be calibrated.

The apparatus is constructed by R. Fuess in Steglitz bei Berlin. [Königsberger expresses a willingness to test the sensitiveness of each instrument and the accuracy of its calibration if it be sent to him for that purpose.]

### GRINDING AND POLISHING.

The ordinary technical and metallographic methods by which a high degree of polish is given to even soft substances, by means of a rapidly rotating disc, yield a streak polish which is entirely useless for these optical measurements, even if for the eye the effect is equal to the more painstaking treatment to be described. In certain soft noncrystalline substances as certain alloys and metals, the polish as commonly obtained may surpass that obtained by the method described below. The use of a polishing steel, as in polishing gold, silver, and other precious metals, or even of hematite, is rarely adapted to crystalline substances, and is certainly open to theoretical objections, since the pressure results in rearrangement of molecules, and increase in density, and therefore a change in optic constants.

If a surface of a large crystal is to be polished for the purpose of exact optical study then an exact orientation is necessary except for isometric minerals. For this purpose I have used the convenient, cheap and precise instrument of E. A. Wülfing[1] with the greatest success. A contact goniometer, accurate to ½ degree suffices for the control; since at present, the optical characteristics of metallic absorbing substances can not be investigated with such precision that a more exact orientation is demanded.

The process of grinding should be accompanied by frequent goniometric measurements to obtain the desired orientation.

[Königsberger made a painstaking research on polishing agents and summarizes his results. He recommends chrome oxide as an efficient polishing abrasive for all minerals, excepting elements and alloys. Chalcopyrite, however, must be treated with a leather impregnated with Paris red in order to reach the highest state of polish.]

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[1] *N. Jahrb. für Min.* 1901. II. p. 1.

The preparation is glued with sealing wax in a warm condition to a thick glass plate with rounded edges. The sealing wax must be spread evenly over the edge, and must present no depressions in which polishing powder could lodge itself.

The surface is ground to approximately the desired size and shape on a rotating polishing plate. Now, if the surface is to be oriented it is fixed to the tripod of the grinding apparatus as described by Wülfing. In order to obviate the hand manipulation of the following operations, the grinding apparatus *A* (fig. 2) is attached to the simple device represented in figure 2. *A* is fixed eccentrically to the axis *B*, which is rotated by the large wheel, *C*. In order to prevent constant polishing of one circle by which the linen is easily torn, the grinder *A* can rotate about its own axis *D*. The axis *D* is inserted loosely into the perforated plate of the grinding apparatus. It is clamped at *E* at the top. Its elevation can be regulated, a lead weight *F* increases the pressure and a lead ring set on a screw transposes the centre of gravity outside the axis *D*. In consequence of this arrangement, a rotation about *B* induces a slower rotation about *D*, and the entire surface *H* is utilized for grinding. *H* is a round glass plate. About this, a frame, which can be tightened by means of a screw is placed. Fine polishing powder is placed on the screw and the surface is ground slightly. Then thinner linen is stretched upon it. This linen must be quite free from knots, and then is ground when moist with the very finest polishing powder. Even at this stage, a lustrous polish may appear, depending on the hardness of the minerals. Usually, however, the polishing must be continued when dry, with the finest twice-washed polishing powder as directed by Le Chatelier.

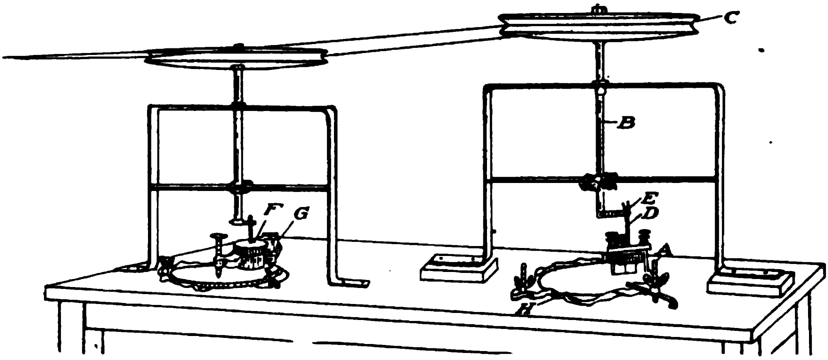

Fig. 2. Polishing apparatus. After Königsberger.

In many cases, the following additional treatment is necessary. On a very finely ground glass plate, fine linen is stretched and carefully washed chrome oxide is employed as a polishing agent. Le Chatelier's device is recommended for washing, or, even better, is an apparatus used for washing and separating soils. Very soft ores—galena, stibnite—are then polished by hand on pear tree wood over which finest linen batiste is stretched. Finally, they are rubbed by a bunch of the same linen. Soft leather also gives excellent results. It is more durable than linen but has the defect that hard bodies from the air becoming lodged in it, destroy the polish, and develop curved surfaces. The capacity of taking on polish does not in all cases (as one might assume) depend on the hardness of the material as it does in the case of iron. By suitable treatment soft stibnite, and hard steel are rapidly polished while galena and hematite take on complete polish only after long treatment, and in the case of several substances perfect polish cannot be obtained. As noted by H. Behrens[1], the penetration of grains of the polishing agent, the passing of the elastic limit, and according to the author's experience, the nature of the fracture and, not least, the microchemical reactions between the polishing agent and the preparation are the most important factors in securing perfect polish.

If the work does not concern crystals which must be studied in definite orientation, then the following simple and time saving grinding apparatus can be used. The substance is fixed on the Plate *A*, as in the preceding description. Then a surface is ground on a rotating polishing plate. Thereupon the plate is fixed at *B*, the screws *C* and *D* are slightly loosened, and the plate is adjusted by hand as nearly as possible parallel to the polishing plate *E*, which is opposite.

This adjustment is made by means of rotations about the two rectangular axes *F* and *G*, which are in a plane normal to the axis of the polishing disc *H*.

The first grinding is done, dry, on firm coarse linen with coarse polishing paper, and then on finer linen with finest, washed polishing powder. Frequently the substance then has perfect polish; otherwise the polishing is continued on the finest linen with washed chrome oxide. Between the successive operations careful cleaning of the apparatus and dusting of its surroundings are necessary. If this is done, any substance or any hand specimen of four square centimeters in size can be ground and polished in three hours. The linen and the polishing agent must be stored separately.

A motor of 1-16 horse power is adequate.

The motor and complete grinding apparatus are furnished by Fuess.

## PART II.

### Objections to the Method.

[Under this heading Königsberger states that the disturbing influence which slight changes in crystal surfaces, caused by striæ, cleavage and twinning planes, have on the reflecting capacity as pointed out by P. Drude[2] and H. du Bois[3] can be overcome entirely by perfecting the polish of the surfaces.]

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[1] *Ann. Ecole Polyt.* Delft. 1887.

[2] *Wied.* Vol. XXXVI. 1889. pp. 549. 886.

[3] *Wied. Ann.* Vol. XLVI. 1892, p. 542.

## Uses of the Apparatus.

The partially described experiments of the following pages are incomplete and can only indicate the special fields of physics and mineralogy in which this apparatus may be useful. The direct application must be left to special research.

### I. Determination of Extinction Angles.

The determination of the relation of optic symmetry lines to crystallographic lines in opaque substances has been accomplished hitherto only by the theoretically and experimentally difficult method of Jamin. With the new apparatus, it is only necessary to introduce the contrast plate and about 10-20 readings are taken on the extinction of the bands. This can be done in 10 minutes. The angle between the line of extinction and the crystallographic direction is determined by the cross hairs. Ten determinations on a cleavage plate of stibnite showed coincidence between optic and crystallographic directions, i. e., an angle of 45° for the extinction angle of the bands, with an error of ± 20′ in measurement.

Observations are made best by taking two readings on the 45° position by approaching this position from the right and left respectively. The exactness of measurement depends on the strength of the anisotropism. [birefringence]. Stibnite has a moderate birefringence on the cleavage surface. This method can therefore be used in determining whether a mineral has monoclinic or orthorhombic symmetry.

### II. Determination of Anisotropic and Isotropic Minerals.

In the case of anisotropic substances all surfaces (excepting a surface perpendicular to an optic axis) must present extinction and reappearance of the Savart bands on rotation of the stage. The delicacy of the method enters into consideration. With the contrast plate, differences of ½% in reflecting capacity can certainly be detected. This corresponds, disregarding the absorption, to a double refraction of 0.6% ($n = 2.5$, mean value for ore). For transparent substances, as is well known, differences of refraction equal to 0.05 can readily be detected with transmitted light, crossed nicols and thin section, and any desired exactness can be obtained through magnification of the actual thickness of the plate. In the method now presented, the limit of exactness is much more restricted, i. e., as stated, 0.6%, since measurement is independent of the thickness of the plate. It is expected therefore that many anisotropic substances will be mistaken for isotropic minerals, however, this is the best method up to date for anisotropic, opaque substances. Sometimes a substance appears isotropic for one color, but not for others. This may be due to the fact that the anisotropic characters for $n$ and $nk$ of a color act in opposite directions, accidentally, and therefore the reflecting capacity which is the resultant of both, gives the effect of an isotropic mineral. This case is parallel to that of a condition present in some rhombic minerals where the optic angle of a certain color is zero. When anisotropism changes sign with wave length change, apparent isotropic conditions may exist in white light. Substances, whose crystals present a close approach to a definite symmetry (as molybdenite and graphite to hexagonal, and chalcopyrite to isometric) also present in their physical properties a close approach to the system simulated. This method will therefore not be decisive in certain absorbing substances, since small differences cannot be detected.

However, in the following cases, this optic investigation will be conclusive:

1. When the symmetry is reached through hidden twinning structure.
2. When crystals with good faces cannot be obtained, the optic investigation affords a more rapid and certain method for determining anisotropism and isotropism, than the study of any other physical property.
3. When crystallographic measurements make it advisable to accept several values for the axial ratio, as well as several positions of orientation, a comparative study of the magnitude and direction of anisotropic characters of related crystals may determine the position of orientation, as for instance, the transparent minerals of the feldspar group. Obviously, the optic axes, i. e., the directions of isotropic reflection in biaxial minerals, cannot be decisive.

As in transparent substances, the optic symmetry (the principal axes of the ellipsoid) in transparent substances, and the value of $n$ and $nk$ in these directions are conclusive. The optic axes, which change their directions for even slight changes in $n$, are not decisive.

A special case is presented by hematite ore. A polished surface parallel to the direction of the fibers showed anisotropism, $I_1 : I_2 = 0.82$. This holds for all surfaces, excepting those perpendicular to the fibers. Here the pleochroic reflection is a result of structure, like the illumination of fibrous minerals in transmitted light between crossed nicols. In general the external form shows whether anisotropism depends on crystal symmetry or fibrous structure. Striation of surface frequently causes anisotropic phenomena. Therefore such surfaces are to be polished very carefully.

A number of additional results are added. A basal cleavage plate of molybdenite is absolutely isotropic; similarly hematite, pyrite, chromite, franklinite, argentite and tetrahedrite are isotropic. The isotropism of graphite parallel to the base is not entirely certain. Pyrrhotite parallel to the base from Morrho Velho appeared on the cleavage surface and the polished surface to be composed of feebly anisotropic parts. Glaucodot is only feebly anisotropic normal to $c$ and is intergrown with a strongly anisotropic, light yellow mineral, namely chalcopyrite. Chalcopyrite, melanite, bournonite and sartorite are anisotropic. Chalcocite is isotropic on the base. Manganite is strongly anisotropic, and columbite, hematite and ilmenite are quite strongly anisotropic.

## THE INVESTIGATION OF METEORITES.

[Königsberger outlines the application of his methods to the study of meteorites.]

## INVESTIGATION OF INTERGROWTHS AND TWIN STRUCTURES OF CRYSTALS.

In many cases this method can be used in determining whether an opaque crystal is homogeneous or compound. The pyrite of Schauinsland may be cited as an illustration. It has a spherical, botryoidal structure. present in most ore samples from this district. They have mostly been identified as pyrite in the past. The polished surfaces show under the microscope that a portion and generally a large connected portion is isotropic, i. e., it is pyrite, while certain lath-shaped, ray-like portions are strongly anisotropic, and are therefore marcasite.

A further illustration is afforded by magnesioferrite from Stromboli. The optical investigation shows that it consists of a feebly reflecting isotropic mass (spinel) and a powerfully reflecting mineral (hematite) whose orientation varies. In marcasite, the complex twin structures are evident at first glance. The varied orientation of the individuals is especially plain. If one individual has been compensated with the aid of the rotating glass plate, the bands are all the more distinct in adjacent individuals. Several marcasite specimens from Leitmeritz are homogeneous. In pyrolusite samples, the varied orientation of the anisotropic needles is readily discerned. A pseudomorph after hematite from Brazil proved to be isotropic.

## INVESTIGATION OF ORE SAMPLES.

The optic study of ore samples is similar to the study of thin rock sections although much less accurate. The first step is the distinction between isotropic and anisotropic ores. For anisotropic ores the relation of the directions of least and greatest reflecting capacity to crystal edges or to cleavage lines must be determined. The latter and the shape of the sections permit the classification into tetragonal, hexagonal, orthorhombic, monoclinic or triclinic ores.

A simple test for uniaxial and biaxial minerals seems impossible at present since parallel light must be employed.[1] On the other hand, the magnitude of the anisotropic reflection for individual minerals is a characteristic parameter. The thickness of the plate is no factor as in transparent minerals in transmitted light. However, the crystallographic position of the ground surface must be known, as in the case of thin sections. The methods of determining this crystallographic position are the same as in the investigation of thin sections; namely, the character of the bounding lines of the surface, and the direction of cleavage. The statistical method of Michel Lévy can also take the place of a knowledge of crystallographic position of the surface. In order to apply such methods it would be necessary to measure the difference in reflecting capacity for a certain color in the principal directions of the most important ores, a task which is not within the author's power. It is merely suggested that for sodium light $R_e : R_a$ for hematite $= 0.881$. $R_0$ is the reflection of the ordinary ray, i. e., for vibrations of the electric (Fresnel) vector normal to the axis *c*. $R_e$ is the reflection of the extraordinary ray. For a cleavage plate of stibnite $R_a : R_c = 0.893$ ($R_a$ = reflection for vibrations of the electric vector parallel to the *a* axis). Some qualitative determinations were begun on other crystals.

Several ore samples were investigated in this manner, for instance, one from Tieftal bei Amsteg in which the tennantite is readily distinguished from associated orthorhombic minerals, which are similar in appearance, by its isotropic nature.

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[1] Phenomena similar to the interference figures, would be observable only in case the loss of phase could be made visible and measurable. Experiments show that this is readily possible, but this anisotropism is very small.

Ore samples from the Alps, which had been under dynamic conditions showed anomalies at times, for example, squeezed galena from Inschialp was slightly anisotropic, whereas galena from other localities is isotropic.

## APPLICATION TO METALLOGRAPHY.

[The application of the new methods to metallographic problems relating to the constitution of alloys, optical relations of isomorphous series, strains and heterogeneity in castings, and the optical properties of electrolytically deposited metals, is discussed by Königsberger, and most fruitful results are anticipated.]

# APPENDIX II.

## *Micro-Chemical Methods.*

*Boricky methods. Use of hydrofluosilicic acid.* The simplest process for the qualitative determination of the alkaline and earthy alkaline elements and the iron of a given mineral is that devised by Boricky by the use of hydrofluosilicic acid. For this purpose a minute piece of the mineral, not larger than the eye of a common needle, and as small as can conveniently be manipulated with the point of a needle, is placed on the surface of a film of hard Canada balsam covering securely a part of the surface of an object-glass. This small piece is then gently covered with a small drop of the acid from the point of a platinum rod. The preparation is then allowed to evaporate entirely, and the surface of the balsam is examined with an objective which has a magnifying power of about 400 diameters. It will be found to be sprinkled over, especially about the edge of the desiccated area, with minute crystallites having perfect forms and polarizing and extinguishing on rotation between crossed Nicols according to the systems to which they belong. These are fluosilicates of the bases present in the mineral. Compounds of sulphur, selenium, tellurium, arsenic and antimony are more or less affected by the same acid.

In order to hasten the drying of the drop lying on the balsam film, which ordinarily will require several hours, the preparation may be placed in a desiccator, over a quantity of sulphuric acid, and enclosed in the reservoir by the cover of the desiccator which will protect it from dust and confine the fumes of the sulphuric acid.

The reagent must be absolutely pure, a drop evaporated on a film of Canada balsam leaving no visible residue, and it must be kept in a small platinum jug. Its strength should be about 3½ per cent. The preparation after drying can be covered with liquid Canada balsam and a thin glass, and preserved indefinitely.

The fluosilicates are identified by their forms. Those of potassium, cæsium and rubidium belong to the *isometric* system. Those of sodium, magnesium and iron to the *hexagonal* system, and those of lithium, calcium and strontium to the *monoclinic.*

The fluosilicates of potassium, sodium, magnesium and calcium can be distinguished at a glance. The micro-crystals of the fluosilicate of lithium are so peculiar as to be easily identified; but those of strontium appear much like those of calcium and are also easily confounded with those of magnesium, or with those of iron and manganese.

Plates I and II, from Boricky's work, show the forms of these fluosilicates when examined under the microscope.

The same kind of tests can be made on a thin rock section. If the section has already been mounted on a microscopic slide, it must be uncovered and freed from any remaining Canada balsam. The drop of the acid is then to be applied carefully to the mineral grain which it is desired to test for the alkalies or alkaline earths.

A platinum foil pierced with a needle, may be so cemented on an uncovered thin rock section that the hole will expose to the action of the acid only the grain over which it is placed. Or, a thin glass cover may be pierced by covering it with Canada balsam, and, after cleaning off the balsam over a small area with a needle, covering the spot with a drop of hydrofluoric acid.

*To distinguish fluosilicate of calcium from fluosilicate of strontium.* Dilute a few drops of pure concentrated sulphuric acid with an equal amount of water, and apply the diluted acid to the crystallites in question. The calcium crystals, after a few seconds, are surrounded by colorless needles of monoclinic gypsum, while those of strontium are slowly dissolved, presenting a few short orthorhombic needles of celestite.

*To distinguish fluosilicates of magnesium, iron and manganese.* This is done by means of chlorine gas, which is developed in a suitable glass vessel by the moistening with muriatic acid, of a small quantity of finely powdered manganese dioxide and applying to the bottom of the vessel a gentle heat over a spirit lamp. The specimens to be examined are supported in the center of the glass vessel by a porcelain frame so as to be enveloped by the gas. The gentle heating should continue about five minutes, with a rapid generation of chlorine gas. The vessel can be covered tightly by a glass plate over the lower side of which has been placed a layer of grease or wax in order to cement it to the rim of the vessel. After the heating the vessel should stand about twenty-four hours, and the heating may be repeated if necessary.

The object-glass carrying the specimens acted on may then be removed and placed in a drying dish for desiccation, when the characteristic crystalline forms will appear. They should, however, be immediately enclosed in Canada balsam and protected by a cover-glass.

It will be seen, on examining the slide, which may have carried the fluosilicates of iron, magnesia and manganese, that those of iron have taken an intense citron-yellow color, while those of magnesium and manganese remain almost colorless. Those of magnesium show a faint gray and are rounded a little at the corners; those of manganese show some tint of red and have suffered more or less dissolution into little prisms, tablets and grains.

The same distinctions between the fluosilicates of iron, magnesium and manganese may be effected by the application of sulphide of ammonium gas, without the application of heat. The specimen (or the object-glass carrying the crystallites) may be enclosed in a glass vessel and covered therein by a glass cover, or simply exposed over the opening of a flask filled with pure sulphide of ammonium. In either case the fluosilicate of iron has become blackish-gray, that of magnesium grayish-white, and that of manganese a peculiar reddish-gray and sometimes disintegrated to a granular mass.

*To distinguish lithia mica, lithia-iron mica and potassium mica.* If these micas be treated with hydrofluosilicic acid the first mentioned will afford tiny six-sided pyramids, sometimes distorted by the abnormal development of two planes, the second shows the same, but accompanied by fluosilicate crystals of iron, and the third will give only hexahedral crystals characteristic of potassium.

A few minerals, such as barite, celestite, rutile, corundum and quartz, are not at all affected by the three per cent. solution of hydrofluosilicic acid, while tourmaline, spinel in thin section, sphalerite and pyrite in fragments, are decomposed by it.

The sesquioxides of aluminum and iron and of some other substances are entirely converted into fluosilicates, but they do not show themselves in crystal forms.

*Use of hydrofluoric acid gas.* This process also produces fluosilicates in the form of minute crystals which do not differ essentially from those already described. A small quantity of the gas is generated in a small platinum crucible on the bottom of which is scattered about half a gram of finely powdered fluoride of barium, with which is also mixed some powdered barium sulphate. Chemically pure concentrated sulphuric acid is then poured into the crucible sufficient to cover the fluoride of barium. The assay pieces of the mineral under examination are to be supported on a perforated platinum plate which is also supported on a platinum wire frame, rising from the bottom of the little crucible. The gas which is liberated from barium fluoride by the attack of the sulphuric acid is to be confined in the crucible by a platinum cover which has been previously covered on the lower side by a film of wax. In order to make it tight upon the crucible this cover is slightly heated and placed on the crucible while the wax is soft. It should be retained in place by a small weight, and the whole apparatus, set aside for about 24 hours, may be covered with a glass tumbler.

The specimen acted upon by the hydrofluoric acid gas is then to be placed in a perfectly clean platinum dish and the dish is to be filled with chemically pure water. The water is to be boiled over a spirit lamp in order to dissolve the fluosilicates that may have been formed, the residue of the specimen removed with perfectly clean pincers, and the water slowly evaporated to a drop which is placed upon the hard balsam surface of an object glass to dry, in a place free from dust. When thoroughly dry the small crystals of the fluosilicates, formed in the process of desiccation, can be examined with the microscope.

The specimen which was boiled in water may be further examined. It may be gently immersed in a drop of sulphuric acid and covered with a thin glass. It is to be observed whether in this process, or even when carefully heated over a spirit lamp, any gas bubbles appear. If none appear then the specimen boiled in water (if a feldspar) contains no remaining metallic fluorides, and the species orthoclase or microcline is indicated.

If, however, the boiled specimen effervesces, even slightly, in the sulphuric acid, the species pertains to the plagioclase group, the rapidity of the evolution of gas and its continuance indicating the proportionate amount of lime contained in the original specimen. Instead of effervescence, however, anorthite shows a slow but strong development of large bubbles of gas. The greater the amount of soda in the original feldspar, the more energetic the effervescence.

*Behrens' method.* The processes devised by Behrens are more complicated and require delicate manipulation. The operation is performed on about half a milligram of the pulverized substance. To this is applied two or three centigrams of hydrofluoric acid, pure and fuming. The fluorides thus formed are dried, and then redissolved in dilute sulphuric acid. This solution is evaporated by heating until the appearance of white vapor fumes of sulphuric acid. If the evaporation is not continued too far the acid serves to retard the too rapid evaporation of the drops in which the different reactions are to be performed.

To the sulphate liquid add an excess of water, and then on a platinum foil evaporate until the volume of the sulphate solution is about one centigram for each milligram of substance attacked.

*Calcium.* If the sulphate contains calcium, on placing a drop of the liquid on an object-glass and allowing it to dry small crystals of gypsum will appear. They may be twinned or single, and sometimes in rosettes, as illustrated by figure 1 below. They measure in larger dimension about 0.6 mm. and can be examined with an objective that magnifies about 150 diameters.

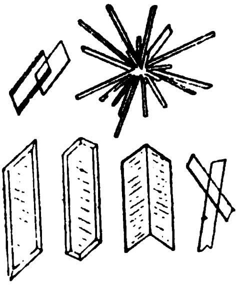

Fig. 1. Sulphate of lime (gypsum). *After Lévy and Lacroix.*

*Potassium.* To a drop of the sulphate liquid add, by means of a platinum thread, a small drop of platinum chloride. After several minutes, if the liquid contains potassium, octahedrons (dodecahedrons or cubes, less frequent) of the double chloride of platinum and potassium begin to appear about the periphery. Alcohol hastens their development. They are bright yellow, isotropic, and very characteristic, sometimes twinned in threes or fours (fig. 2), and have strong refraction.

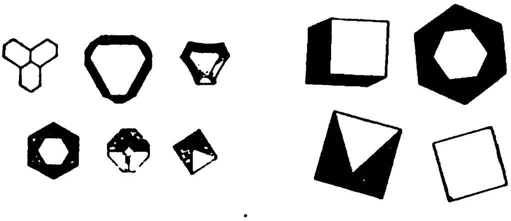

Fig. 2. Potassium platinic chloride. *After Lévy and Lacroix,* and from the *American Geologist.* Vol. XXVI. Plate XVIII.

*Sodium.* If a drop of the acid sulphate liquid contain sodium it can be shown by adding a drop of sulphate of cerium. The latter is to be placed at about 5 millimeters from the drop of the sulphate liquid, and the two are to be brought together through a capillary glass tube which will unite them. In the cerium sulphate drop will spring up little clusters of brown crystals of the double sulphate of cerium and sodium visible when magnified about 600 diameters. If the original liquid contain also potassium the double sulphate of that alkali forms larger grains, from 0.05 to 0.06 mm. in diameter, at the center of the other clusters. These are grayish. If the liquid contain a large excess of sulphuric acid it gives rise to large radiating rosettes of acid sulphate of cerium which obscure the reaction sought.

*Barium and strontium.* These are precipitated with the calcium by drying the liquid. When heated with concentrated sulphuric acid they are dissolved. Then by cooling and the addition of water they recrystallize in the form of spindles crossing at right angles. The twins of sulphate of barium have dimension of 0.05 to 0.012 mm. Those of strontium reach even 0.45 mm.

The inconvenience of this process is that the sulphate of lime accompanies the other sulphates during all the manipulation. It is precipitated more slowly than they, and they can be seen to appear in succession thus: sulphate of barium, then of strontium, and finally that of calcium.

*Magnesium.* Place a drop of the sulphate liquid near a drop of water containing salt of phosphorus and unite them with a capillary glass thread. If the solution contains more than 1 per cent. of magnesium there are developed forms forked in opposite directions of the size of 0.6 mm. in length. If the liquid is more dilute it gives rise to beautiful orthorhombic hemimorphic crystals which resemble the roof of a house.

Iron and manganese phosphates give the same crystals, but they may be separated by previous addition of ammonia.

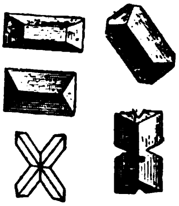

**Fig. 3.** Ammonium magnesium phosphate. *After Lévy and Lacroix.*

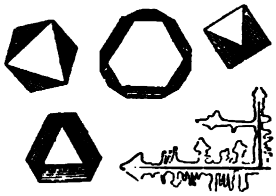

**Fig. 4.** Cæsium alum. *After Lévy and Lacroix.*

*Aluminum.* Use cæsium chloride. From the sulphate solution carefully expel any excess of the acid. Into a drop of the solution place the end of a platinum thread previously dipped in melted cæsium chloride. It is only necessary to touch the surface of the drop to see large crystals of cæsium alum arise. They are octahedrons and cubo-octahedrons sometimes 0.9 mm. in size (fig. 4). Iron can be disregarded as its alum forms more slowly.

Behrens gives numerous other micro-chemical reactions for the determination of sulphur, phosphorus, chlorine, fluorine, silica, and boron. For these the student is referred to Judd's translation, published by Macmillan in 1894. But Behrens' latest work (Mikrochemische Technik, 1900) is available only in the original.

### *Some Special Tests.*

Optical methods of determining minerals are now so numerous and exact that it is only rarely necessary to have recourse to these microchemical methods. But in certain cases the latter became important. The following will serve as illustrations:

Analcite may be distinguished from opal and leucite by its gelatinization with acids. The gelatinous silica thus produced is not readily recognized microscopically, but it may be rendered very distinct by staining. This is accomplished by gently washing off the attacking acid without disturbing the silica formed, then applying some staining liquid, as an aniline color, allowing to stand, and gently washing off the excess staining liquid.

Calcite may be distinguished from dolomite and magnesite by tests revealing the relative amounts of calcium and magnesium present according to the methods already described, and also by noting the different effects when treated by acids. Thus, calcite dissolves in acetic acid with abundant evolution of carbon dioxide, while dolomite is attacked very slowly, and magnesite not at all. This difference may be increased by adding ammonium phosphate to the reagent used. Linck[1] has suggested that the proportion of phosphate to acetic acid to water be 2 : 3 : 10. In this case, if the carbonate contains as much as 10 or 15 per cent. of $MgCO_3$, the magnesium phosphate precipitated on the surface will soon stop the attack by the acid altogether. Magnesite is not attacked even by cold hydrochloric acid. Siderite is difficultly distinguishable from calcite by optical methods. It is acted upon slowly by cold acids; rapidly by hot hydrochloric acid. The iron may be made manifest by adding to the solution potassium ferricyanide which gives a deep blue color. Or, if ammonium sulphide be added, a black precipitate is produced. The process may be simplified by atttacking the carbonate with acid already containing the precipitating reagent.

Sodalite may be distinguished from other similar minerals by attacking the surface with very dilute nitric acid containing a little silver nitrate. Sodalite is readily attacked, yielding gelatinous silica and chlorine, which produces with the silver a cloudy precipitate of silver chloride in the silica. Haüynite may be distinguished from sodalite by attacking the mineral with hydrochloric acid, and evaporating to dryness, when calcium sulphate (gypsum) crystals will form in the gelatinous silica. Noselite may be distinguished from sodalite by attacking the mineral with hydrofluoric acid containing a little barium chloride; the barium sulphate crystals formed reveal the presence of sulphur in the mineral attacked.

Talc may be distinguished from muscovite by igniting the mineral with cobalt nitrate which imparts a pink color to the talc.

Graphite (and carbonaceous matter) may be distinguished from other opaque black minerals by heating the section to redness, when the carbon will go off as the oxide.

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[1] Inaug. Dissert. Strassburg. 1884.

## EXPLANATION OF PLATES.

### PLATE I.

Fig. 1. Fluosilicate of potassium, × 400; e. m. n. r. produced by hydrofluoric acid gas; s. t. are crystals formed by recrystallization of fluosilicate of ammonium.

Fig. 2. Fluosilicate of potassium, × 400; produced by hydrofluoric acid gas; from amazonite.

Fig. 3. Fluosilicate of lithium, × 200; recrystallized on the object-glass.

Fig. 4. Fluosilicate of sodium, × 400; produced by hydrofluoric acid gas; from albite.

Fig. 5. Fluosilicate of calcium, ×150.

Fig. 6. Fluosilicate of calcium, × 200.

Fig. 7. Fluosilicates of sodium and of calcium, × 200.

Fig. 8. Fluosilicates of sodium and calcium, × 200.

Fig. 9. Fluosilicate of strontium, × 200, by recrystallization upon an object-glass.

Fig. 10. Fluosilicate of magnesium, × 600; from chondrodite.

Fig. 11. Fluosilicate of magnesium, × 400; from humite.

Fig. 12. Fluosilicate of magnesium, × 400; from magnesite.

Fig. 13. Rare crystals, probably of calcium, × 400; from corsite, tankite.

Fig. 14. Fluosilicate of barium, and branching forms of fluosilicate of calcium, × 400; brought out only by breathing upon them; treatment with hydrofluosilicic acid; from witherite.

Fig. 15. Fluosilicate of iron, × 400; by recrystallization upon the object-glass.

Fig. 16. Fluosilicate of potassium, × 400; on a thin section of amazonite, preserving the lattice structure of the amazonite.

Fig. 17. Fluosilicate of sodium and a few spindle forms of the same of calcium, × 400; from oligoclase.

Fig. 18. Fluosilicate of sodium (in bubbles) and of calcium (in lenticular forms) × 400; from labradorite.

Fig. 19. Fluosilicates of sodium and calcium, × 400; from labradorite.

Fig. 20. Fluosilicates of sodium and calcium, × 400; from anorthite.

### PLATE II.

Fig. 1. Fluosilicate of sodium, × 400, and wedge-shaped etchings, on albite.

Fig. 2. Fluosilicates of potassium and sodium, and a single rod of calcium, × 400; from leucite.

Fig. 3. Fluosilicates of sodium and potassium, × 400; from elæolite.

Fig. 4. Fluosilicates of calcium and sodium, × 400; from scapolite.

Fig. 5. Left half. Fluosilicates of lithium, potassium, iron and calcium. × 400; from lithia mica.

Right half. Fluosilicates of potassium, sodium, and iron, × 400; from potassium mica.

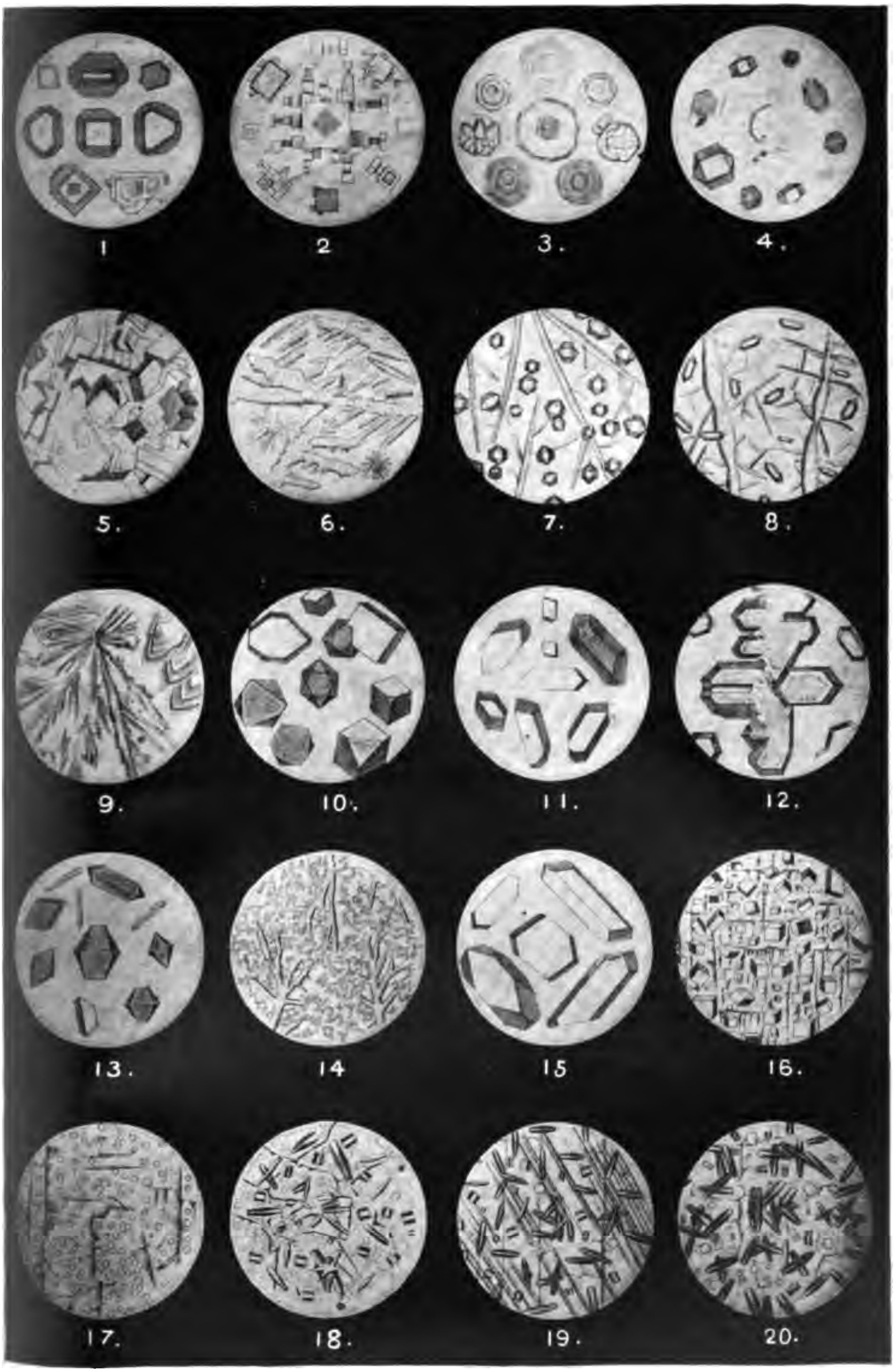

**PLATE I.**

**Boricky Micro-chemical method.**

Fig. 6. Fluosilicates of potassium, magnesium, and calcium, × 400; from biotite.

Fig. 7. Fluosilicates of magnesium, iron, calcium, and sodium, × 400; from amphibole.

Fig. 8. Fluosilicates of calcium, magnesium and iron, × 400; from diallage.

Fig. 9. Fluosilicates of magnesium and iron, × 400; from bronzite.

Fig. 10. Fluosilicate of magnesium, × 400; from dichroite.

Fig. 11. Fluosilicate of magnesium and iron, × 400; from olivine.

Fig. 12. Fluosilicates of magnesium (× 200) and iron (× 600-800); from olivine.

Fig. 13. Section of chiastolite, $\perp c$ × 200-400; no distinct crystallites; bars and spots arranged according to the structure.

Fig. 14. Etchings on lithia iron mica, after boiling in water, × 400.

Fig. 15. Chloride of sodium; long, wrinkled etchings and two cleavage clefts; from elæolite.

Fig. 16. Fluosilicate of calcium (after boiling in water) and small hexagonal crystals of apatite, × 600; from apatite, cut || base.

Fig. 17. Etchings on section of apatite, cut || prism face, boiled in aqua regia, and prominent edges of pyramidal crystals, × 600.

Fig. 18. Section of apatite, cut || base, treated with chlorine gas, × 400; dark needles probably remnants of the edges of the uppermost stratum of subindividual crystals, with long adherent bubbles of air; amongst these are faint outlines of the individual crystals of the next lower stratum.

Figs. 19 and 20. Sections of apatite, cut || base treated, with chlorine gas, × 400; shows the internal structure of apatite, made up of subindividual crystals of apatite mainly parallel to the axis.

Of the foregoing the following were treated with hydrofluoric acid gas:

Plate I. Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 15, and plate II, fig. 14.

The following were treated with hydrofluosilicic acid:

Plate I. Figs. 11, 12, 13, 14, 16, 17, 18, 19, 20, and plate II, figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 16.

The following was treated with both hydrofluoric acid gas and hydrofluosilicic acid:

Plate I. Fig. 10.

The following were treated with chlorine gas:

Plate II. Figs. 15, 18, 19, 20.

And one was treated with *aqua regia*, viz., plate II, fig. 17.

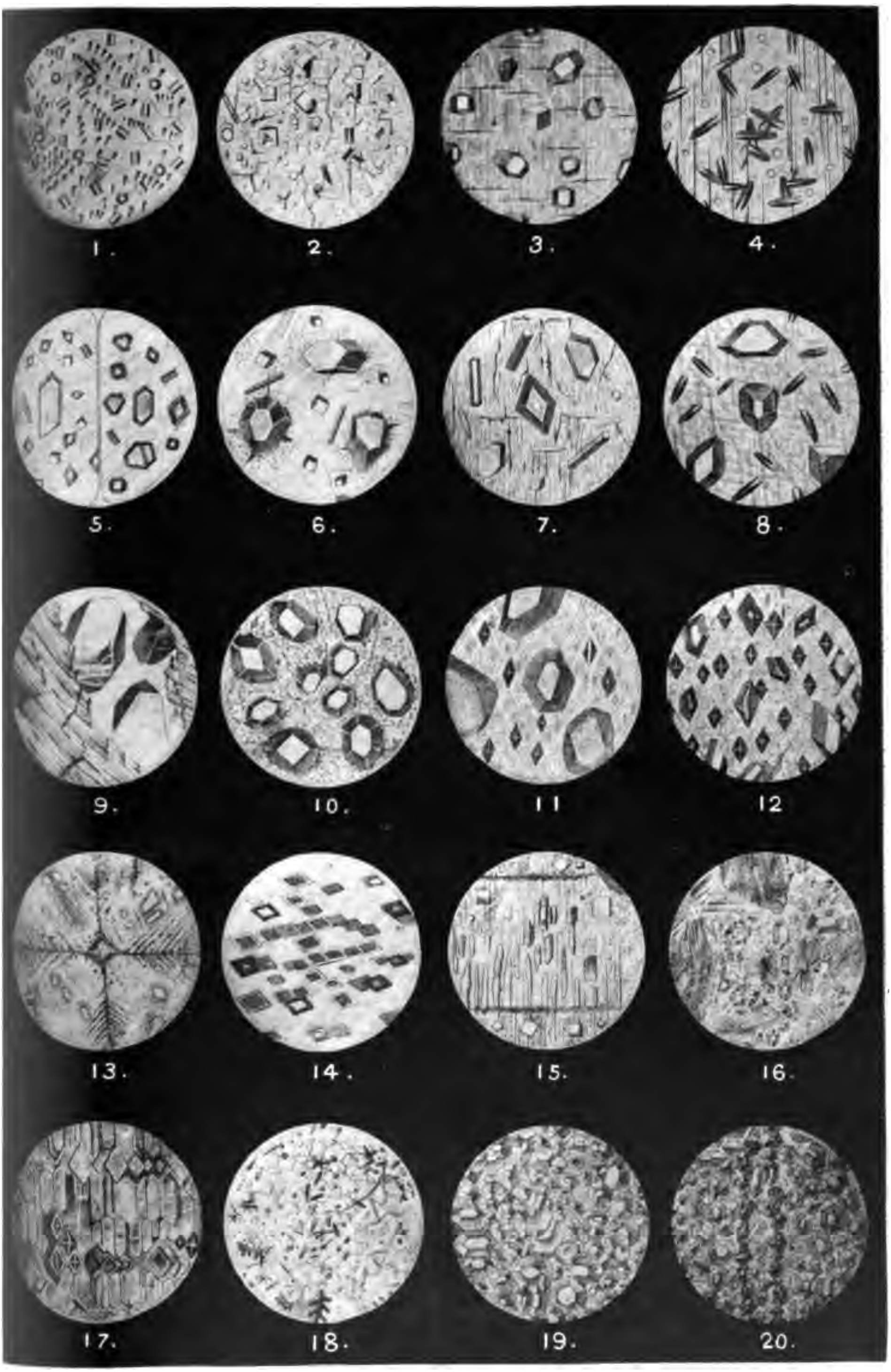

**PLATE II.**

**Boricky Micro-chemical method.**

# APPENDIX III.

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# ADDENDA.

**Interference of simple waves.** If two waves are travelling along the same path and vibrating in the same plane with a fixed phase relation they combine (or "interfere") to form a wave whose character depends upon the wave lengths, the amplitudes, and the phases of the original waves. The resultant wave is readily constructed for any simple case.

If the two waves have the same wave length and the same phase with differing amplitudes the resultant wave will have an amplitude equal to the sum of the amplitudes of the component waves, as in fig. 1. (See page 489).

If the two waves have the same wave length and same amplitude and differ in phase by half a wave length the resultant wave will disappear since its amplitude will be the difference of the amplitudes of the component waves, or zero, as in fig. 2.

If the two waves have the same amplitude and different wave lengths the difference of phase will vary along the path, and the resultant wave may be illustrated by fig. 3. This explains the indistinctness of interference colors of the higher orders.

If the two waves have the same wave length, unequal amplitudes, and a phase difference of one-half wave length, the resultant wave will have an amplitude equal to the difference (or algebraic sum) of the amplitudes of the component waves, as in fig. 4.

If the two waves have the same wave length and the same amplitudes with a phase difference of one eighth or one quarter of a wave length, the resultant wave will have an amplitude equal to the algebraic sum of the amplitudes of the component waves, as in figs. 5 and 6.

Put in still more general form, the wave resulting from the combination (or "interference") of any two waves may be found by drawing each with its proper wave length, amplitude, and phase, and constructing the resultant wave from the points determined by taking the algebraic sum of the corresponding ordinates of the component waves at different points along the path, as in fig. 7. The construction and form of the resultant wave become more complicated with more than two component waves. Hence the wave of white light is extremely complicated, since it is composed of waves of a great variety of wave lengths. This complex form of wave is present in all our *ordinary* light, including that derived from the sun.

**Sign of elongation.** The sign of elongation of a uniaxial mineral is usually the same as the sign of the mineral, (since it is usually elongated parallel with the vertical axis.). But in some rare cases (for example, basal plates of hematite and of apophyllite) the elongation is in all directions normal to the vertical axis, in which case the sign of the elongation is the reverse of the sign of the mineral. In general, in uniaxial crystals the sign of the elongation depends upon which axis of ether vibration is parallel with the direction of elongation, being positive when Z is parallel with the elongation and negative when X is parallel thereto.

The sign of elongation of biaxial minerals may be +, ±, or —, depending upon whether Z, or Y, or X is nearest to the axis of elongation.

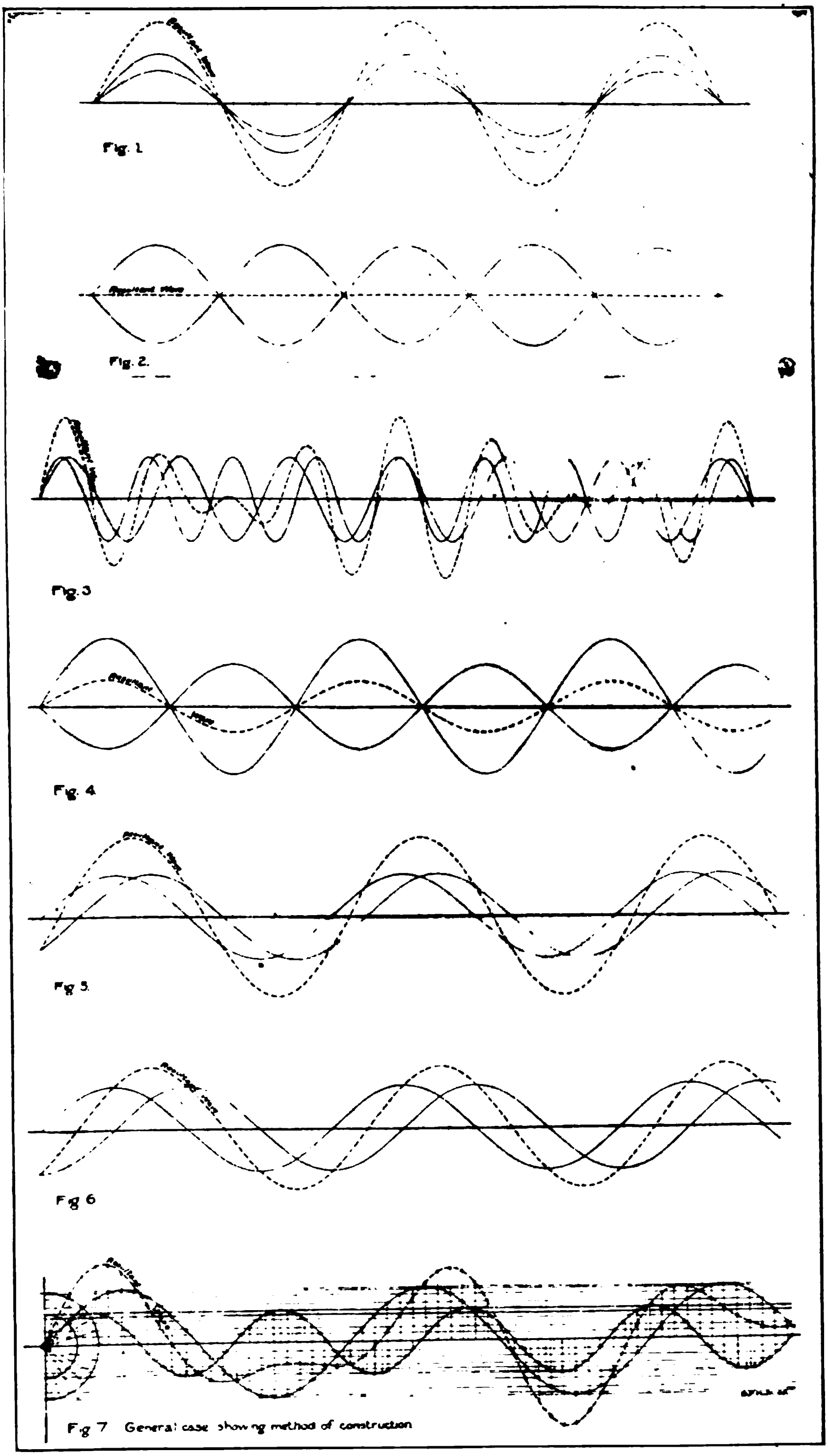

Fig. 1

Fig. 2.

Fig. 3

Fig. 4

Fig. 5.

Fig. 6

Fig. 7 General case showing method of construction

**Figs. 1-7. Interference of Simple Waves.**

The sign of elongation is positive when Z is nearest to (or coincides with) the axis of elongation. When a mineral is elongated parallel to Y the sign of the elongation is positive in some sections and negative in others. If an orthorhombic section be elongated parallel to Y and to *c* a macropinacoidal section may be normal to Z, and, if so, the elongation is positive. A brachypinacoidal section of the same mineral would be normal to X and have negative elongation. This variation of sign is due to the fact that the ray vibrating parallel to Y travels faster than the Z ray, but more slowly than the X ray.

Further, in monoclinic and triclinic crystals in which the direction of elongation is usually not parallel to any one of the axes of ether vibration, the sign of the elongation is determined by that axis of ether vibration which is nearest the axis of elongation. Thus, all pyroxenes have positive elongation when the angle between Z and *c* is less than 45°. (See fig. 167, page 324.)

In the case of minerals which exhibit flattening (or elongation parallel to a plane) all sections except those parallel to the plane of flattening will exhibit an apparent elongation whose direction will be variable, depending upon the direction in which the section is cut. In this case the sign of elongation is determined by the relation in position between the axes of ether vibration and the normal to the plane of flattening. The sign of elongation is positive when X is nearest the normal to the plane of flattening, ± when Y is so situated, and negative when Z is nearest. Thus, all micas have positive elongation, since X is nearly normal to the basal flattening in all species.

ACTION OF QUARTZ WEDGE. The accompanying diagram (page 491) illustrates clearly the action of the quartz wedge in increasing the relative retardation of one ray as compared with the other, when inserted so that its axes of ether vibration are respectively parallel to the similar axes of ether vibration of a mineral section, and its action in decreasing the relative retardation when inserted so that its axes of ether vibration are respectively parallel to dissimilar axes of the mineral section. The mica plate and sensitive tint plate act in a similar way, but do not have an increasing effect due to varying thickness, as is obtained on inserting the quartz wedge, thin edge, first.

Plate III is a reproduction of Michel Lévy's Table of Birefringences in which rock forming minerals are arranged on the basis of their maximum interference colors, without regard to any other characters.

In plate IV all minerals microscopically identifiable are platted on the basis of refringence and birefringence. This diagram was suggested by the one prepared by W. O. Hotchkiss[1], which is limited to rock forming minerals, and in which such minerals are platted on the basis of refringence alone. Plate IV was drawn under our direction by Mr. W. G Weber. The chief purpose of these plates is to aid in the identification of minerals.

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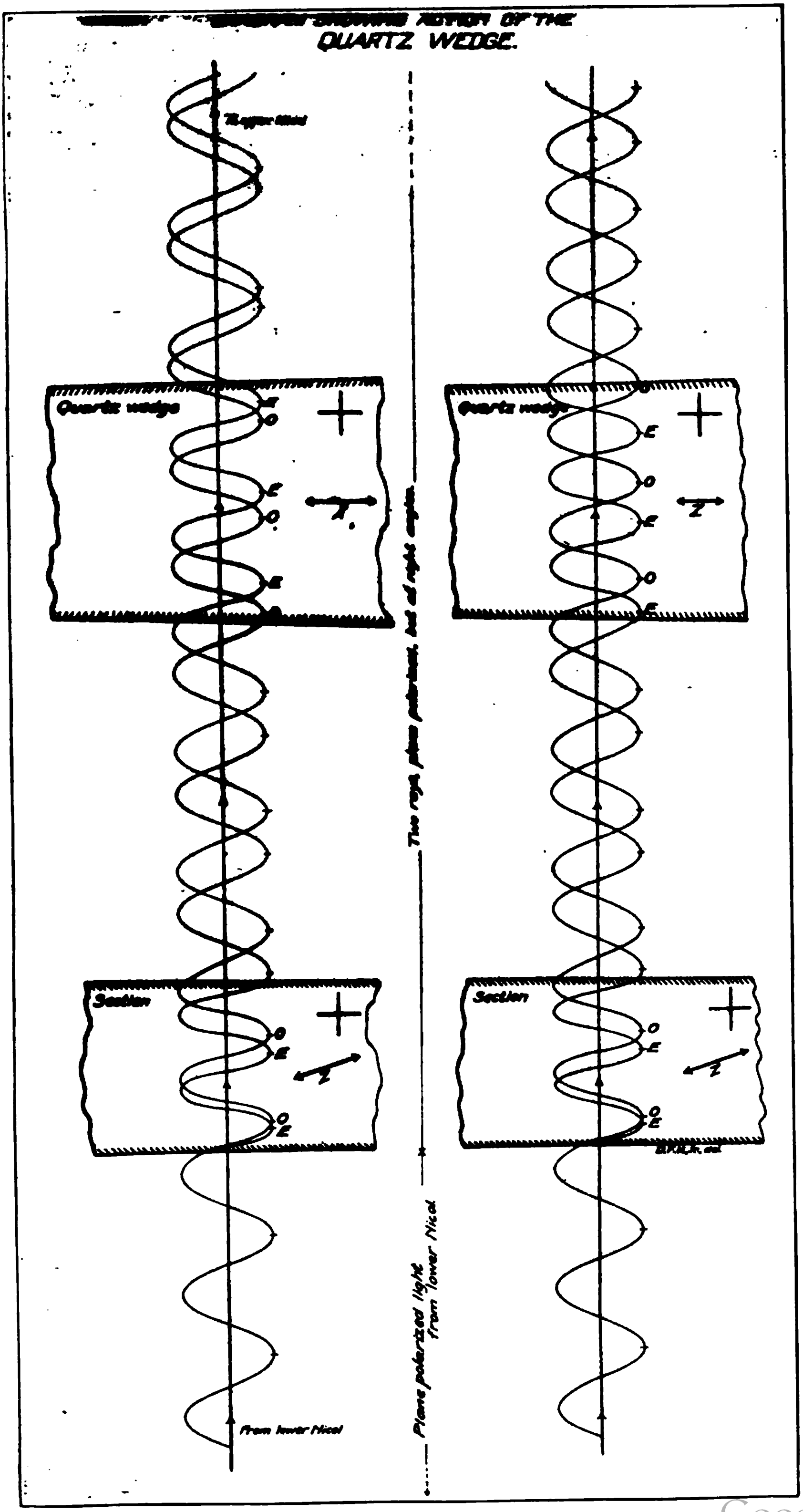
[1] *Jour. Geol.* XVI. 1908. p. 421.


[illegible] SHOWING ACTION OF THE QUARTZ WEDGE.
To upper Nicol
Quartz wedge
E
O
E
O
E
O
Z
Quartz wedge
O
E
O
E
O
E
Z
Section
O
E
O
E
Z
Section
O
E
O
E
Z
B.W.L. Jr. del.
From lower Nicol
Two rays, plane polarized, but at right angles.
Plane polarized light from lower Nicol

Action of the Quartz Wedge.

# ERRATA.

Page 7, line 7. Add "for small angles."

Page 46, line 5 from bottom. Read: "extraordinary," instead of "extrordinary."

Page 48, line 13. Read: "*F Q*," instead of "*G Q*."

Page 48, line 22. Read "*G Q*," instead of "*F Q*."

Page 55, figure 58b. The *E* ray should be shown refracted to the *other* side of the *O* ray for a positive mineral, as cassiterite.

Page 61, line 8 from bottom. The equation should read:

$$d = \frac{1128-575}{707-345} = 1.52+$$

Page 65, line 6. Read: "tardation in," instead of "fraction of."

Page 79, line 18. Read: "to an acute bisectrix," instead of "to a bisectrix."

Page 84, line 15. Read: "Z or X," instead of "Z or Y."

Page 179, after line 12, the following paragraph was omitted:

**Lepidocrocite** has about the same composition as gœthite; **it has** perfect cleavage || 010, imperfect || 001 and 100. The optic plane is parallel to 100; the acute bisectrix X is normal to 010; the optic angle is large, without abnormal dispersion. Absorption $Z > Y > X$, and Z brownish yellow, Y orange yellow, X clear yellow, in sections a little too thick. Usually associated with limonite.

Page 423, line 2. Read: "Subtranslucent," instead of "Subtarnslucent."

Page 458, line 21. Read: "Staurolite," instead of "Straurolite."

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Where there are several page references black faced numerals are used to designate the chief description.

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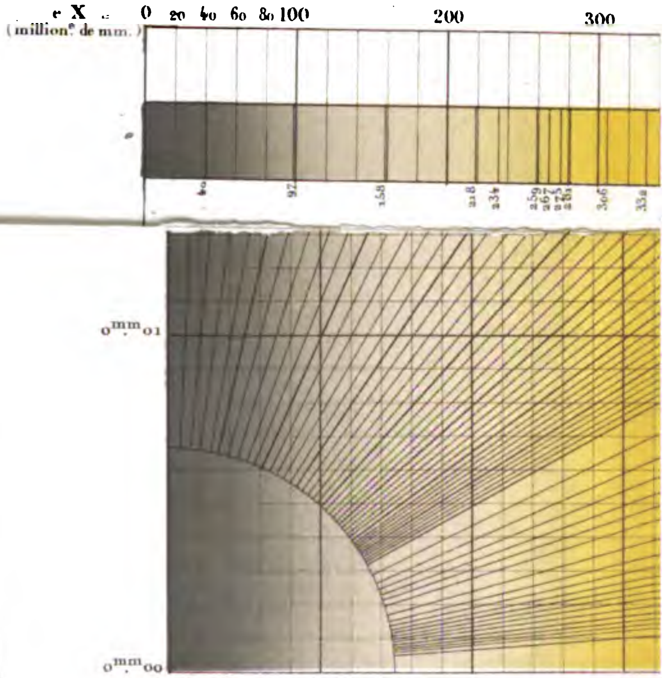

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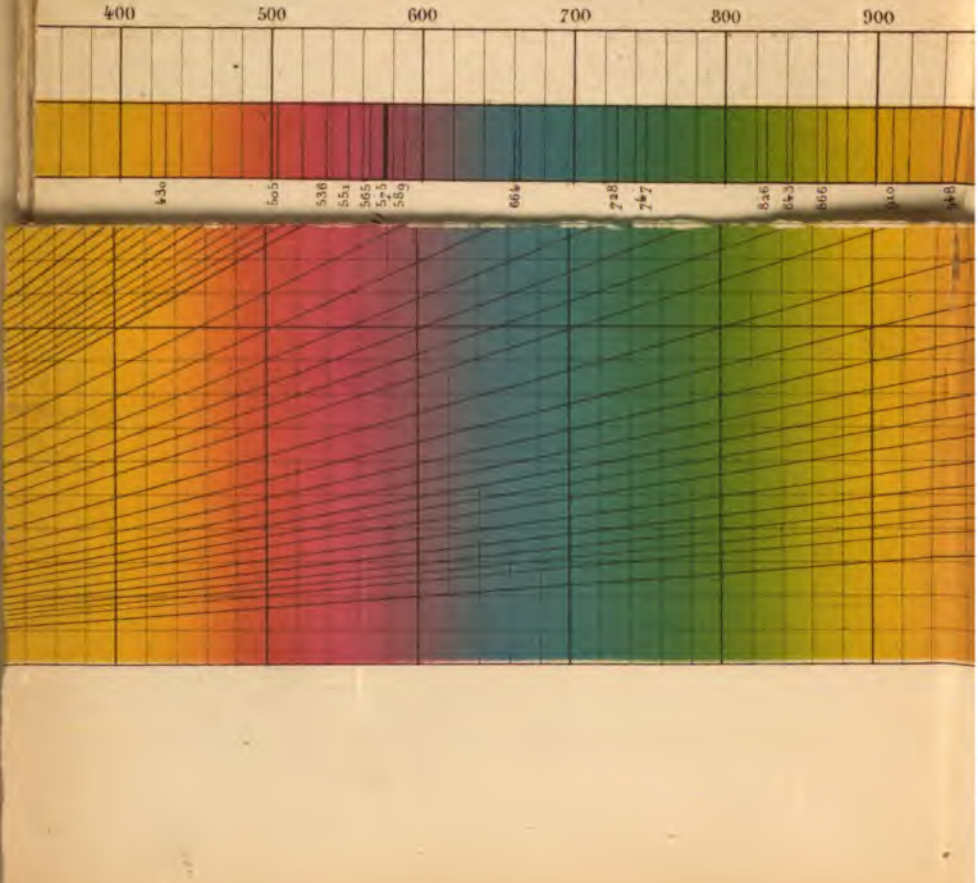
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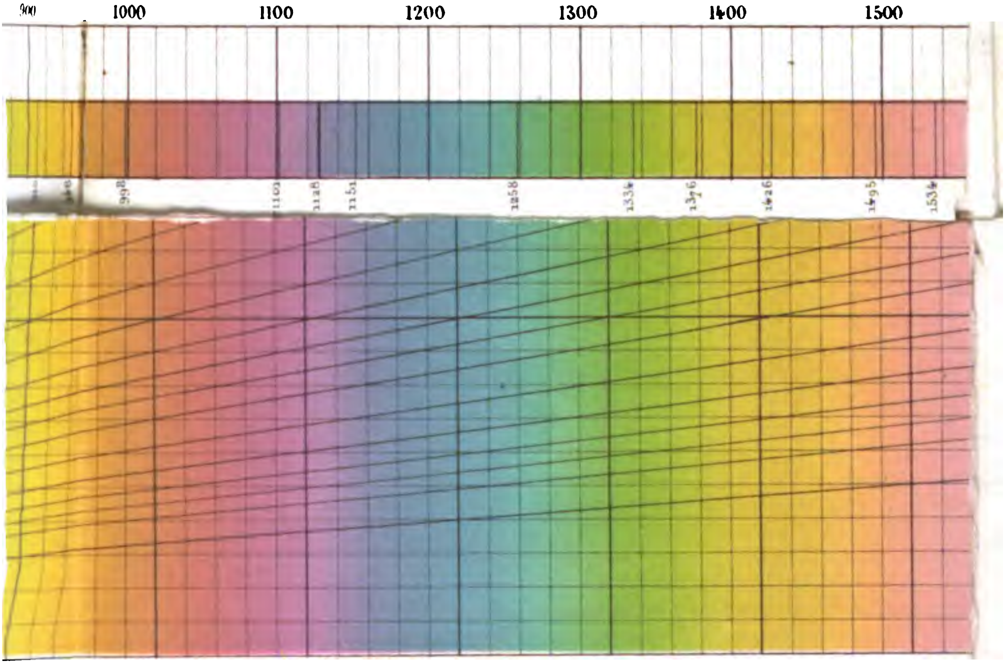

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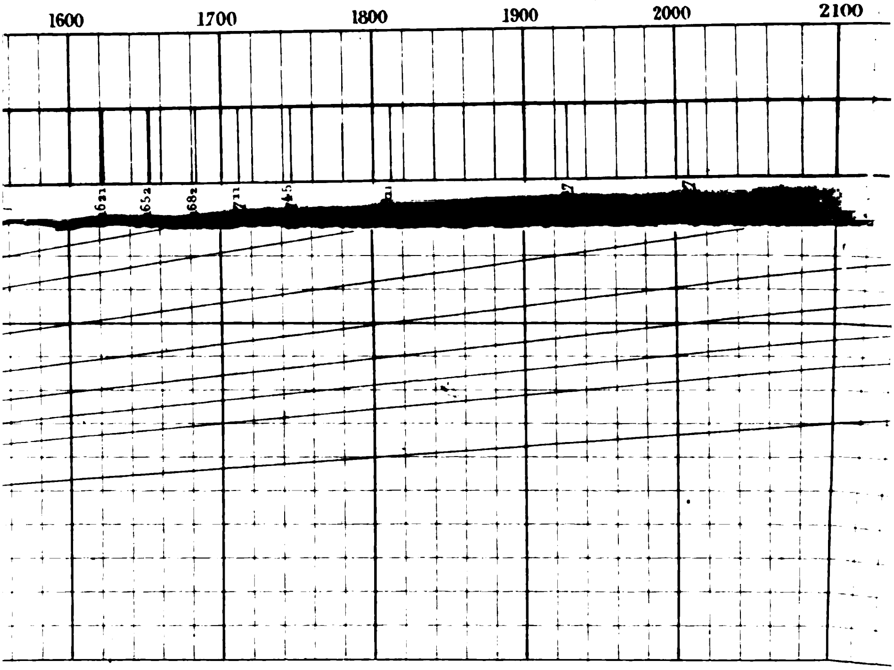
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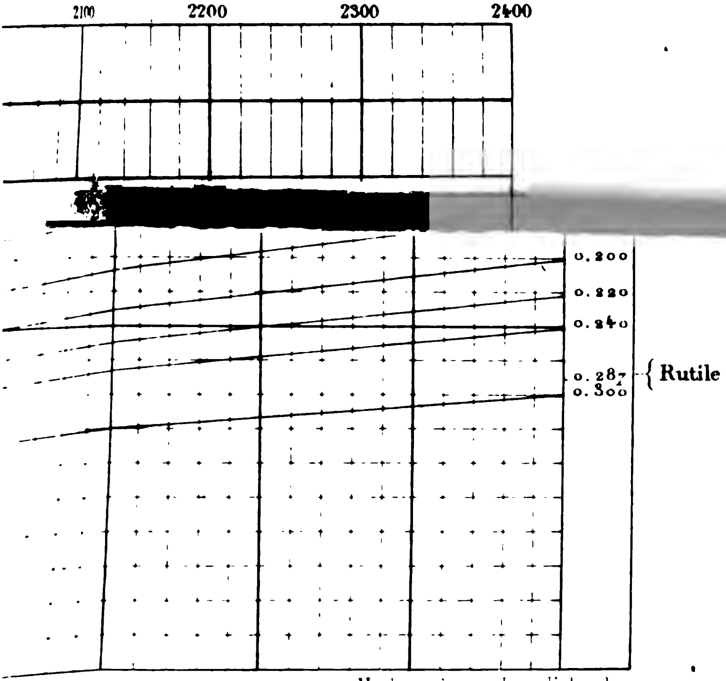

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